UNIVERSITY OF NAIROBI

SIMULATING IMPACTS OF CLIMATE CHANGE ON SORGHUM PRODUCTION IN THE SEMI-ARID ENVIRONMENT OF KATUMANI IN MACHAKOS COUNTY, KENYA

BY

EMILY NYABOKE BOSIRE

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DECLARATION

I, the undersigned, hereby declare that this PhD thesis is my original work, except where duly acknowledged and has not been presented for a degree in this or any other university.

Signature……………………………………….. Date…………………………..
Emily Nyaboke Bosire
180/50271/2015
Department of Meteorology,
University of Nairobi

This PhD thesis has been submitted with our approval as university supervisors.

Signature……………………………………….. Date…………………………..
Dr. Fredrick Karanja
Department of Meteorology,
University of Nairobi

Signature……………………………………….. Date…………………………..
Dr. Gilbert Ouma
Department of Meteorology,
University of Nairobi

Signature……………………………………….. Date…………………………..
Dr. Wilson Gitau
Department of Meteorology,
University of Nairobi

DEDICATION

This PhD thesis and all the efforts that were put forward into developing it is dedicated to my husband, Herbert and daughter Kaylee whose love, support and prayers kept me going. My parents Mr. and Mrs. Dominic Bosire, brothers, sisters and friends this work is also dedicated to you.

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ABSTRACT

Reduced agricultural production and food security continues to be pressing problems for the larger part of smallholder farmers in Sub-Saharan Africa (SSA), as well as semi-arid Eastern Kenya. The main objective of this study was to assess the potential impacts of climate change on sorghum production in the semi-arid environment of Katumani in Machakos County, Kenya. The study sought to determine the effect of current and future climate and agronomic practices on the growth, development and yield of two sorghum cultivars. It also evaluated different farm-level adaptation strategies that may improve the adaptive capacity of sorghum growing farmers in the face of climate change. The study was conducted in National Dryland Farming Research Centre at Katumani, in eastern parts of Kenya.

The variability and trends of climate parameters and sorghum yields were determined using coefficient of variation, linear regression and Mann-Kendall test. The findings show that in the study area, the MAM season is characterized by high variations in seasonal rainfall compared to the OND season, but with low variability in both seasonal and annual temperatures. Additionally, higher variability (45%) in sorghum yield was noted. The results also showed insignificant trends for the intra seasonal rainfall characteristics. However, significant decreasing trends of rainfall at seasonal and annual scales were recorded at Iveti and Machakos DO station. Positive significant trends for maximum and minimum temperatures were noted at annual scale. Sorghum trend depicted positive insignificant trends.

Field experiments were conducted to determine the effect of different cultivars, nitrogen and phosphorus levels on the growth, development and yield of sorghum. The experiments were laid out in a randomized complete block design with two replications over four seasons. The analysis of variance showed non-significant effect of nitrogen (N) and (P) on phenological parameters of sorghum, growth parameters (biomass) and yield. However, the parameters were influenced by cultivar effect. The interactive effect of N, P and cultivar in the four seasonal experiments were non-significant for all the parameters.

The Agricultural Production Systems sIMulator (APSIM) model was calibrated and evaluated for growth, development and yield response of sorghum to inorganic nitrogen fertilizer. Modified index of agreement, coefficient of determination and root mean square error were used to determine the level of agreement between the observed values and model simulated values. Model evaluation results pointed out that APSIM has a propensity to slightly over estimate the phenology, growth and grain yield. However, the error in all the parameters was below 15%, which is judged acceptable.

Model performance of the CORDEX GCMs was assessed using modified index of agreement and root mean square error. Three models (CanESM2, GFDL-ESM2M, NorESM1-M) and the ensemble performed relatively well in simulating the observed climate variables over the study region. Thus, these models were applied in the modeling of impact of climate change on sorghum production.

The simulated impacts of climate change on sorghum production in Machakos County were assessed using percentage mean changes and coefficient of variability. Both RCP 4.5 and 8.5 show an increase in temperature and rainfall compared to the 1976-2005 baseline period. Projected mean changes on phenological parameters showed a consistent decline for both sorghum varieties during both the long and short growing season. The end century (2070-2099) showed the greatest shortening in the phenological dates. There was also slightly greater variability in the phenological dates under current climate than under climate change during the MAM season. There was slight increase in biomass for both varieties under climate change with the application of fertilizer. It has been noted that under changing climate sorghum grain yields will consistently increase for both cultivars over different time periods with up to 85.3% increase towards the end of the century (2070-2099). Yields of both cultivars are more variable under current climate than under climate change and thus they can be predicted with more confidence in the future.

APSIM model was able to predict the response of sorghum to climate change and, from the results attained, changing the plant density (increase to 88,888 and decrease to 53,333 plants ha^{-1}) as an improved agronomic practice was proposed. Results indicate that phenological dates were increased with increase in plant population and vice versa. These dates were less variable (less than 20%) for both plant populations under both the base period and changed climate. Biomass weight for both cultivars was found to increase and decrease for the highest and lowest plant population, respectively. Higher and lower grain yield were recorded from highest and lowest plant populations, respectively during the OND, but for MAM growing season, the reverse happened. The variations of biomass and grain yield increased with increase in plant population and vice versa.

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ABREVIATIONS AND ACROYNMS

AGRA	Alliance for a Green Revolution in Africa
AIC	Agricultural Information Center
AIM	Asian Pacific Integrated Model
AMP	Annual amplitude in mean monthly temperature
ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems sIMulator
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
ASALs	Arid and Semi-Arid Lands
ASON	August-September-October-November
BMA	Bayesian Model Averaging
CanESM2	Second Generation Canadian Earth System Model
CCCma	Canadian Centre for Climate Modelling and Analysis
CCSM3	Community Climate System Model Version 3
CEC	Cation exchange capacity
CERES	Crop-Environmental Resource Synthesis
CFS	Climate Forecast System
CGCM3	Third Generation Coupled Global Climate Model
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM-CERFACS	Centre National de Recherches Meteorologiques
CNRM-CM5	Centre National de Recherches Meteorologiques Coupled Model version Five
CPI	Climate Prediction Index
CO_2	Carbon dioxide
CORDEX	Coordinated Regional Downscaling Experiment
CSIRO Mk2	Commonwealth Scientific Industrial Research Organization Mark 2b model
CV	Coefficient of Variability
d	index of agreement

DAE	Days after emergence
DAS	Days after sowing
d_m	Modified index of agreement
DUL	Drained Upper Limit
EABL	East African Breweries Limited
EC-EARTH	Europe-wide Consortium EARTH
ECHAM	European Centre Hamburg Model
EOF	Empirical Orthogonal Function
EPIC	Environmental Policy Integrated Climate
ESAANet	East and Southern Africa Agribusiness Network
FAO	Food and Agricultural Organization
Finert	Proportion of soil carbon assumed not to decompose
Fbiom	Proportion of decomposable soil carbon in the more labile soil organic matter pool
FURP	Fertilizer Use Recommendation Project
GCAM	Global Change Assessment Model
GCMs	Global Climate Models/ General Circulation Models
GDD	Growing Degree Days
GDP	Gross Domestic Product
GFDL	Global Fluid Dynamic Laboratory
GHA	Greater Horn of Africa
GISS	Goddard Institute of Space Studies
GoK	Government of Kenya
HadCM2	Hadley Centre Coupled Model, Version 2
HadCM3	Hadley Centre Coupled Model, Version 3
HadGEM2-ES	Hadley Centre Global Environmental Model version 2 Earth System configuration
ICHEC	Irish Centre for High-End Computing
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute

IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre-Simon Laplace
JGCRI	Joint Global Change Research Institute
JJAS	June-July-August-September
K	Potassium
KALRO	Kenya Agricultural & Livestock Research Organization
KMD	Kenya Meteorological Department
KNBS	Kenya National Bureau of Statistics
LL15	Lower Limit of extraction by the crop at 15 bar metric pressure (Wilting point)
LSD	Least Significant Difference
MAM	March-April-May
MAMJ	March-April-May-June
ME	Model Efficiency
MESSAGE	Model for Energy Supply Strategy alternatives and their General Environmental impacts
MIROC5	Model for Interdisciplinary Research on Climate version 5
MoA	Ministry of Agriculture
MOHC	Met Office Hadley Centre
MPI-M	Max Planck Institute for Meteorology
MPI_ESM_LR	Max Planck Institute Earth System Model running on low resolution grid
MRI	Meteorological Research Institute
N	Nitrogen
NARL	National Agricultural Research Laboratory
NASA	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research
NCC	Norwegian Climate Centre

NEPAD	New Partnership for Africa's Development
NH_4	Ammonium
$(NH_4)_2HPO_4$	Diammonium phosphate
(NH_4NO_3)	Ammonia nitrate
NIES	National Institute for Environmental Studies
NorESM1-M	Norwegian Earth System Model 1-Medium resolution
NO_3	Nitrate
OND	October-November-December
OSU	Oregon State University Model
P	Phosphorus
PAR	Photosynthetically Active Radiation
PBL	Planetary Boundary Layer
PDFs	Probability density functions
pH	Negative logarithm of soil ion concentration
POWER	Prediction of World Energy Resources
R^2	Coefficient of determination
RegCM2	Second-generation regional climate model
RCA4	Rossby Centre Regional Climate Model
RCBD	Randomized Complete Block Design
RCPs	Representative Concentration Pathways
REA	Reliability ensemble averaging
RMSE	Root mean square error
RT	Rainfall Totals
RUE	Radiation Use Efficiency
UKMO	United Kingdom Meteorology Office
UKTR	United Kingdom Transient Model
UNDP	United Nation Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
WCRP	World Climate Research Program

WFP	World Food Programme
SAT	Saturated volumetric water
SDGs	Sustainable Development Goals
SMA	Simple model averaging
SoilN	Soil nitrogen module in APSIM
SOILP	Soil phosphorus
SoilWAT	Soil water module in APSIM
SRES	Special Report on Emissions Scenarios
TAV	Annual average ambient temperature

CHAPTER ONE

INTRODUCTION

1.1 Background Information

High levels of atmospheric gases within the atmosphere, caused by both natural and anthropogenic (human) activities, are the primary driver of the changing climate being experienced in most regions of the world (Forster *et al*. 2007). It is predicted that these changes would have both negative and positive impacts on diverse economic sectors of any country. These sectors include agriculture, tourism, energy, water resources, forestry, fisheries, and health (Hanson *et al*. 2007; IPCC 2007). However, due to the size and sensitivity of the agriculture sector across the world, it is largely affected by the impacts of climate change (Kurukulasuriya and Mendelsohn, 2008; Mendelsohn, 2009). In Africa the extent of damage on agriculture is dependent on future scenarios of climate change and the type and amount of farm inputs used for crop production (Dimes *et al.*, 2008; Mendelsohn, 2009).

In spite of innovative advances in agriculture, for example, high yielding crop varieties and more efficient irrigation systems, agricultural practices still highly rely on climate. On global scale the most dominant climate variables affecting crop yields are rainfall and temperature (Lobell and Field 2007; Lobell *et al*., 2011; Ray *et al*., 2015), and thus variability of these climate variables results to inter-annual variation in crop yields (Matiu *et al*., 2017). Previous studies on climate change on crop production have indicated likelihood of impacts being negative rather than being beneficial to crop yields (Rosenzweig and Parry, 1994; Lobell *et al*., 2011; Lobell and Guordji, 2012), with the decreased crop yields being partially compensated by internal economic responses (Nelson *et al*., 2014). These impacts on agricultural practices especially on food production are worldwide concerns especially in developing countries, including Kenya, where its population depends mainly on rainfed agriculture for food requirements. This reliance of Kenya’s population on rain fed agriculture makes her food security highly exposed to the risks linked to climate, hence making adaptation to climate change a great necessity.

In Kenya, Agriculture continues to be the most important sector contributing approximately 26 percent of the country’s Gross Domestic Product (GDP) and accounting for approximately 65 percent of the country’s total exports. Approximately 18 and 70 percent of the employed population in the formal and informal sectors of Kenya, respectively, are within the agricultural sector (GoK, 2009; GoK, 2010). Bumper harvest in agricultural production especially the cereals is vital in future as an assurance of food security, income and improved livelihoods to the population living in both rural and urban areas.

Production of cereals in the arid and semi-arid lands (ASALs) is increasingly being threatened by several factors including declining soil fertility, land degradation, limited fertilizer application, use of non-certified seeds, low adoption of drought resistant crops and increasing variability in seasonal rainfall (Kinyua, 2004; Alemu and Bayo, 2005; Mwangi and Mundia, 2014). If these factors are tied to the projected increase in population, rapid urbanization and the ever decreasing arable land, agricultural production and food security in semi-arid Eastern Kenya will be seriously threaten (Muhammad *et al*., 2003; Recha *et al*., 2013. Thus cereal production will have to be enhanced so as to meet the increased demand. Detailed analysis of these factors is vital for sustainable increase in cereal production under a variable and changing climate.

For enhanced and sustainable agricultural production in ASALs such as Machakos County, improving soil fertility and promoting drought tolerant and escaping crops and/ or "orphan crops" for example sorghum, which are known to be well adapted to harsh climate, are crucial to better cope with the impacts associated with the changing climate (Obia, 2011). "Orphan crops" are those crops which are bought and sold locally and capable of playing a significant role in sustaining regional food security (GoK, 2009).

Sorghum (*Sorghum bicolor (L) Moench)* is a C_4 plant and is economically ranked as the third most imperative cereal crop after maize (*Zea mays*) and wheat (*Triticum aestivum*) in Kenya (AGRA, 2013; MoA, 2013). It is a crop that is drought resistant and performs well on a wide scope of poor soils with low amount of rainfall, regularly out-yielding most cereals in hot and dry environments. Comparing sorghum with other cereals such as maize, low input requirements are needed for its production. Sorghum grows rapidly with high fodder dry matter content, high grain yielding ability and high nutritional quality. In Kenya it is principally adapted to agro-ecological zones which are classified as ASALs in nature. These include the former Rift Valley, Nyanza, Western and Eastern provinces (Kameri- Mbote, 2005, Muui *et al*., 2013). These provinces accounted for approximately 7, 9, 41 and 43%, respectively, of Kenya's total sorghum production in 2011 (MoA, 2012). Utilization of sorghum is similarly restricted to these growing areas.

Sorghum is a regularly consumed food by over 0.5 billion people in over 30 countries, mainly in the developing world (Kumar *et al*., 2011). It is an extremely important crop for the poverty-stricken and food insecure people and is predominately grown in ASALs (Timu *et al.*, 2012; USAID 2010). Approximately 55% of the sorghum produced in the world is used as food (Africa Harvest, 2010). About 74% of sorghum produced in Africa is consumed at home, mostly in the form of thick or thin porridges, or as traditional beer (ESAANet, 2013).

Sorghum production in Kenya has been consistently declining over the years. The decrease in production may be attributed to climate and several production constraints including competition from other cereal crops principally maize, soil infertility, reduced farm holdings, pests and diseases, bird feeding damage, weed competition, and low adoption of enhanced production technologies (Opole *et al*., 2007). The decline of major crops which include sorghum results in higher public expenditure on food imports (GoK, 1997; Kameri-Mbote, 2005).

The impact of climate change on sorghum prevalence in Machakos County remains unknown owing to the fact that there is uncertainty in the Global Climate Models (GCMs) to predict climate variables especially rainfall. Projections from the GCMs proposes that in future variability in climate is anticipated to increase thus extreme weather events may turn out to be more persistent and severe in the Sub Saharan countries (Cooper *et al*., 2008; Field, 2012; Omondi *et al*., 2013). This might lead to food insecurity and also increase exposure of the community to impacts of climate change because of low adaptive capacities. Extreme weather events like floods and droughts, which are triggered by climate variability and climate change, are more frequent in the ASALs of Kenya, making the communities in the ASALs to be at higher risks to variations in climate (McCarthy *et. al.,* 2001). These extremes have profound impacts on agriculture, which is the driver of Kenya’s economic growth. Thus the importance of analyzing the projected impacts of climate change on agricultural production so as to expand on the distress of food security and making sure that repercussions of the impacts are communicated to public and policy makers (IFPRI, 2009; IPCC 2007; Cooper *et al*., 2006). This will aid in the formulation of appropriate plans to reduce the impacts of climate change or adapt them.

Despite the large uncertainties of GCMs particularly at local scale due to their coarse resolution (Murphy *et al*., 2004; Dessai *et al*., 2005; Fu and Charles, 2007), they have consistently provided credible simulations of climate (Carmen Sa´nchez de Cos *et al*., 2013). The utilization of GCMs projections at a finer resolution has continued to be the focus for assessing climate change impacts on various sectors such as the agricultural and hydrology (Rosenberg, 1992; Izaurralde *et al*., 2003).

Prior to evaluating future projections, it is important to assess the performances of the GCMs in simulating climate variables with regard to observed data. Conventionally the agreement between observed data and model data is merely the way to assign considerable confidence into the superiority of a climate model (Errasti *et al*., 2011), assuming that if a climate model accurately reproduces the current climate, the higher its reliability in the projection of the future climate (Giorgi and Mearns 2002; Coquard *et al.*, 2004). However, it is recognized that GCMs simulate different variables differently and that there is no particular model which performs best for all the variables and/or regions (Lambert and Boer, 2001; Gleckler *et al*., 2008). Hence when studying the relationship between crop production and climate change, it is important that outputs from more than one GCM be used to run the crop models so as to get better results (Guerena *et al*., 2001; Izaurralde *et al*., 2003).

Different types of crop models have been developed and have the ability to reproduce the interactive effects of climate and soil on the yields of any crop in diverse farming systems. Agricultural Production Systems sIMulator (APSIM) is one of the crop models and was chosen to simulate sorghum growth and development in this research. This crop model was developed for regions which are semi arid and has been broadly used in smallholder farming systems in the same regions. APSIM has been confirmed to be a helpful tool in examining the probable impacts of climate change on crop production (Keating *et al*., 2003; Wu *et al*., 2006; Wang *et al*., 2010). Prediction of crop yields using crop models has reduced the risk of crop failure in totality or considerably reduced yields since faster results and greater understanding of the crop dynamics can be obtained more quickly.

1.2 Problem Statement

Depleted soil fertility is among other factors that have severe limitations to small scale crop production and to sustainable food security in the ASALs (Alemu and Bayo, 2005). The depletion of soil fertility levels is attributed to constant cultivation of the same piece of land and the low usage of inorganic fertilizers among smallholder farmers (Gachimbi *et al*., 2002; Tittonell *et al*., 2005). Hence smallholder farming in the ASALs is portrayed by low external farm input, deminishing crop yields and food insecurity (Stoorvogel *et al*., 1993; Rhodes, 1995; Mafongoya *et al*., 2006).

The ASALs for example Machakos County are generally dry, making rainfed agriculture difficult. This situation is further worsened by recurring and persistent droughts occasionally extending for two-to-three years continuously, hence exhausting any surplus food within the county (Ongeko, 2011). These have hindered efforts to improve the food security situation in the County (Mwandalu and Mwangi, 2013). In the last two decades, maize crop has been persistently failing in several parts of eastern Kenya particularly because of mid-season droughts (Nagarajan and Audi, 2007). Such low agricultural production has led to increase in the level of poverty, thus the dependence on relief food for human survival has increased within the County. From the County's total population, approximately 59.6% lives below the national poverty threshold (GoK, 2011).

The long term solution towards enhancing food security, income growth and poverty alleviation in the ASALs is by increasing production within the agricultural sector. Inorganic fertilizers can be used to replenish the soil nutrients in the ASALs. The worry is that there is limited information regarding the response of sorghum to inorganic fertilizer (Nitrogen and Phosphorus) in the study area due to limited research. In addition the effects of climate variability and change that is likely to result in increase in extreme events posses another challenge (IPCC, 2007).

This research therefore under took a study on the effects of two cultivars and different nutrients application rates on sorghum production and afterward assessed the potential impacts of climate change on sorghum production.

1.3 Research Questions

1) What are some of the past observed variability and trends of the climate parameters and sorghum yields within the study area?
2) Does the cultivar choice and application of different rates of Nitrogen and Phosphorus have any statistical significance on the growth, development and yield of sorghum?
3) How well does the APSIM model simulate the growth, development and yield of sorghum planted in different seasons?
4) What is the accuracy of GCMs within the Coordinated Regional Downscaling Experiment (CORDEX) in simulating the past climate (precipitation, temperature and solar radiation) over the study area?
5) What are the likely impacts of climate change on growth, development and yield of sorghum under given specific climate change scenarios?
6) What type of agronomic management practices can be suggested in response to the impacts of climate change?

1.4 Hypotheses

1) There are no significant trends for the climate parameters and sorghum yields within the study area.
2) There is no significant difference in the effect of cultivar and application of different rates of Nitrogen (N) and Phosphorus (P) on growth, development and yield of sorghum.
3) The APSIM model will not be able to simulate the growth, development and yield of sorghum planted in different seasons.
4) GCMs within CORDEX will indicate low level of agreement with the observed past climate (precipitation, temperature and solar radiation) over the study area.
5) The expected future increase in mean temperature, changes in rainfall patterns and variability of extreme weather events will not make significant changes to sorghum growth and sorghum grain yield as compared to the baseline climate data.
6) The agronomic management practices adopted will not significantly improve the development, growth and yield of sorghum.

1.5 Objective of the Study

The overall objective of the research was to determine the potential impact of climate change on sorghum growth, development and yield under different nutrients management in semi-arid environments with special emphasis on Katumani in Machakos County, Kenya.

To achieve this, the following specific objectives were undertaken:

1) To determine the effect of variability and trends of climate parameters (rainfall and temperature) on sorghum yield.
2) To determine the effect of cultivars, Nitrogen and Phosphorus application rates on the growth, development and yield of sorghum planted in different seasons.
3) To calibrate and assess the capability of APSIM-Sorghum model in simulating the growth, development and yield of sorghum planted in different seasons.
4) To assess the performance of CORDEX GCMs in simulating climatic parameters (precipitation, temperature and solar radiation).
5) To assess the impacts of climate change on the growth, development and yield of sorghum using APSIM-Sorghum model.
6) To evaluate different agronomic management practices to reduce the impact of climate change on the growth, development and yield of sorghum.

1.6 Justification of the Study

There is an agreement that climate change is real and that various economic sectors inclusive of agriculture will be affected under the changing climate. The damaging impacts of climate change are mostly expected in Africa with the communities in the rural setting being highly exposed to the risks associated with climate change. It is also anticipated that the existing adaptation strategies against climate change that farmers are using may not compensate the impacts of changing climate. These call for preventive measures to be considered in order for agriculture to continue playing its fundamental task of supporting and sustaining the national economies in Africa and making certain that regions within the continent are food secure.

There is need to study the climate-crop relationships under changing climate conditions because climate variables (solar radiation, temperature, and precipitation) affects plant growth and development. It is essential to understand the manner in which climate change will affect the productivity of crops and its biophysical systems (Sangpenchan, 2009) because probable impacts of climate change may be advantageous or harmful on agricultural production due to extreme events, or increased CO_2 fertilization. This is fundamental to facilitate appropriately inform adaptation.

The best opportunity available for people living in the ASALs to manage the negative effects of climate change is by growing of drought tolerant and high yielding short duration crops (Miano *et al*., 2010). The Ministry of Agriculture has been supporting this approach by promoting the implementation of “orphan crops or minor crops” (such as sorghum and millets) as part of its strategy to revive agriculture and to ease chronic food insecurity in ASALs (GoK, 2009).

Sorghum being a resilient crop is seen as the crop for the future because it can adapt well to the high temperatures and the uncertainty in rainfall, which are projected as possible in the future. Improved sorghum varieties, if grown in semi-arid areas like Machakos County, can survive and yield well in such erratic rainfall conditions. Sorghum is not only a subsistence crop but it can be used as a cash crop due to the increased demand by brewers and the World Food Programme (WFP) for making beer and for relief supplies, respectively. Sorghum is expected to alleviate hunger and poverty and transform drought prone areas into bread baskets through stabilization of household food production and in the long run the income of smallholder farmers.

This study sought to assess the potential impacts of climate change on sorghum production at a local scale and find possible ways of enhancing food production in Machakos County in tandem with increased population growth. This will allow for the achievement of the Rio+20 declaration addressed by Sustainable Development Goals (SDGs) 1 and 2 (no poverty and zero hunger), the NEPAD’S Initiatives on “Food for All”, and the planned Kenyan 2030 vision of transforming Kenya to self reliance in food production.

Results generated from this research will contribute to better understanding of impacts of climate change on sorghum production and also improve the welfare of the sorghum dependent communities. These results can provide a baseline for the formulation of efficient and precise strategies to assist farmers to control, manage and familiarize themselves to the impacts associated with changing climate.

1.7 Study Area

1.7.1 Location

The area of study was Machakos County which borders Nairobi and Kiambu, Embu, Kitui, Makueni, Kajiado and Murang'a and Kirinyanga counties to West, North, East, South West and North West, respectively. The County comprises of four sub-Counties, that is, Machakos, Kangundo, Mwala and Yatta (Figure 1). It covers an area of approximately 6,208 km^2 with an estimated human population of 1,335,387 according to the 2009 Kenya population and housing census and the projected annual growth rate of 2.47% (KNBS, 2010). The experimental site selected for this study was the National Dryland Farming Research Centre at Katumani. The Katumani Research Centre (01°35'S; 37°14'E, 1600m) is located in the dry lowlands of Machakos County in the semi-arid Eastern Kenya. It is located in the transitional agro-climatic zone IV/V (Jaetzold and Schmidt, 1983).

Machakos County was selected for this study because in comparison with other ASALs in the country, the County has the potential to feed itself remarkably when compared to the Counties in the northern parts where crop production is intensely inhibited by hot and dry climate and the livelihoods of the community are restricted to pastoralism (Thiongo *et al.*, 2016). Hence the county is superior in depicting observable response to climate related hazards. In comparison to other Counties in the central and southern parts of the country, the County's close proximity to the country's capital city was an added advantage, which allowed for ease of access to the research station.

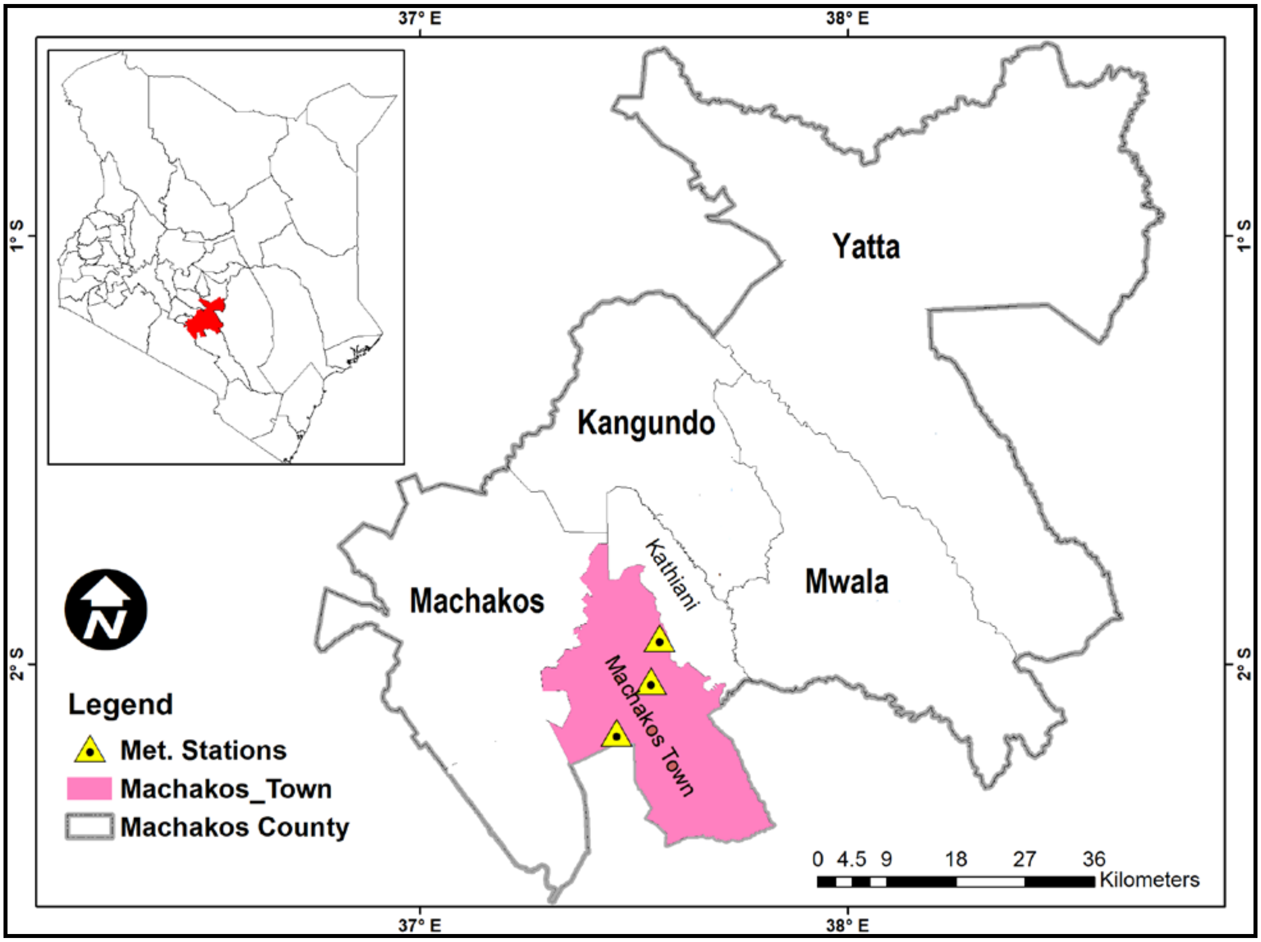

Figure 1: Map of Machakos County, showing the four sub-counties and the meteorological stations used in the study

1.7.2 Climate

The study area experiences a semi-arid tropical climate characterized by hot days and cold nights with temperatures varying from a mean annual minimum and maximum of 13.7^{o}C and 24.7^{o}C, respectively (Wamari *et al*., 2012). It has a bimodal rainfall pattern, the long and the short rainfall seasons, which occur from March to May (MAM) and from October to December (OND), respectively. The average seasonal rainfall for the long and short rains is approximately 277mm and 300mm, respectively (Shisanya *et al*., 2011), while annual mean is approximately 655mm (Wamari *et al*., 2012). The short rains in semi-arid parts of Kenya are more reliable, uniformly distributed and sufficient for crop production. On the other hand, the long rains are connected with nearly all crop failures due to its unreliability, poor distribution and insufficiency for crop production (Biamah *et al*., 1993).

1.7.3 Soil Type

The soils at Katumani are said to be crusting sandy clay loams and are classified as Chromic Luvisols (FAO/UNESCO Classification in 1990). This type of soil always portrays a quick breakdown in its aggregates when exposed to strong rainstorm events because of its unstable structure owing to low organic matter content in the soils. The most common problems related to this type of soil include soil crusting, degradation of soil structure, soil erosion, seasonal soil water deficits, soil erosion and depleted soil fertility.

1.7.4 Agricultural Farming in the County

Regardless of the climatic and environmental challenges observed in the county, agriculture is fundamental in the economy. It is leading sector with regard to food security, employing approximately 73% of its population and contributing approximately 70% to household income earnings (Gichagi *et al*., 2015; Machakos County, 2015). The commonly known factors that have limited agricultural production in the county include; high cost of inputs (fertilizer and hybrid seeds), few extension services, shortage of markets, over reliance on rain fed agriculture and limited use of agricultural technology and innovation (such as enhanced crop varieties and irrigation systems). The agricultural production in the County is mostly small scale and mainly for subsistence. It's dominated by cereals, pulses and root crops (Table 1).

Table 1: Crop production in Machakos County by the year 2012

Crop	**Acreage in Hectare**	**Grain yield (90 kg bags)**	**Grain yield (kg/ha)**
Dry Maize	149,338	1,092,210	658.2
Sorghum	11,539	54,758	427.1
Beans	75,025	397,572	476.9
Millet	20,191	149,010	664.2
Cow peas	34,710	168,812	437.7
Green grams	13,873	62,895	408.0
Pigeon peas	50,302	274,874	491.8

Source: Kenya Economic Review of Agriculture, 2012

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of literature on modeling impacts of climate change on sorghum production. Specifically the variability and trends of the climate parameters was first reviewed, followed by global climate models and assessment of their skills, general information and agronomic features of sorghum, an overview of Agricultural Production Systems sIMulator (APSIM) Model, previous related research on the use of APSIM model and lastly the impacts of climate change on sorghum production.

2.2 Variability and Trends of Climate Parameters

Understanding the dimensions of the monthly, seasonal and inter-annual variability of temperature and rainfall over an area will result to better quantification of their impacts particularly on crop yields. This will allow for the best adaptation measures to be suggested (Tamiru *et al*., 2015).

Rainfall amount and its distribution within a growing season greatly affect crop production in most parts of the world. It dictates the types and varieties of crops to be grown, the possibility of irrigation and it also influences agricultural calendar. Onset and withdrawal of seasonal rainfall in East Africa have generally received less attention from the scientific community compared to the seasonal rainfall totals (Nicholson, 2017).

Several studies have examined trends in the climate variables across eastern Africa (Camberlin and Okoola, 2003; Seleshi and Zanke, 2004; Tilahun, 2006; Mugalavai *et al*., 2008; Njiru *et al*., 2010; Recha *et al*., 2012; Wagesho *et al.*, 2013; Kansiime *et al*., 2013; Omondi *et al.,* 2013; Opiyo *et al*., 2014; Omoyo *et al*., 2015).

Tilahun (2006) analysed the temporal variation of rainfall in the arid and semi-arid regions of Ethiopia. Nine (9) meteorological stations were considered. The start of the study period was different for the stations having data ranging from 1953 to 1970 and ending in 2002. The study revealed relatively high inter-annual variability of rainfall.

Camberlin and Okoola (2003) characterized the inter-annual rainfall variability of the onset and cessation dates of the East African long rains (MAM) for the period 1958 to 1987. The data used was for stations within Kenya and North Eastern Tanzania. They observed larger the inter-annual variability of the onset dates compared to the cessation dates.

Mugalavai *et al*. (2008) analysed the onset, cessation and duration of the growing seasons for both MAM and OND seasonal rainfall in Western Kenya using daily data ranging from 15- 34 years. They observed high and low variability of the onset and cessation dates, respectively. On the other hand, the variability of the length of the season was relatively higher as compared to the onset.

Recha *et al*. (2012) determined the variability of seasonal rainfall, onset and cessation in Tharaka District, Kenya. Daily rainfall from three stations; Tunyai (1973 to 2006), Chiakariga (1974 to 1999) and Marimanti (1969 to 1997) were employed in the study. Though both MAM and OND seasonal rainfall were highly variable, the within season variability during MAM season was high. The results also indicated that the onsets were highly variable on an annual scale than the cessation dates.

Kansiime *et al*. (2013) assessed rainfall variability and trends in Eastern Uganda for the period 1971 to 2010. The results indicated that the highlands (lowlands) areas depicted increasing (decreasing) amounts of rainfall and higher (lower) variability within and between seasons. Variation was greater for August to November (ASON), than March to June (MAMJ) season for all the locations. The results also depicted significant positive trends in the seasonal and annual rainfall for the highlands areas and insignificant decreasing trends for the low lying areas.

Seleshi and Zanke (2004) examined changes in rainfall totals and the frequency of rainy days in Ethiopia over a period of 1965 to 2002. They considered eleven (11) stations and two seasons (JJAS and MAM) within the study area. The results depicted no trend in the seasonal rainfall, annual rainfall and the rainy days over Central, Northern and North West Ethiopia. However, the annual rainfall and the JJAS seasonal rainfall showed significant decreasing trends (95% confidence level) over Eastern, Southern and South West stations. Trends in the rainy days were generally less consistent.

Wagesho *et al. (*2013) characterized spatial and temporal variability of seasonal and annual rainfall in Ethiopia using 0.5° by 0.5° gridded monthly precipitation data for the period 1951 to 2000. JJAS seasonal rainfall and the annual rainfall exhibited significant decreasing trends (90% confidence level) in the Northern, North West and Western parts of Ethiopia. However, a few grid points in eastern regions show increasing annual rainfall trends. Most other parts within the study region exhibited insignificant trends. The contrasting results between the two authors could be attributed to the different lengths of data used, type of data and the significance level employed.

Opiyo *et al*. (2014) analysed temporal trends of rainfall and temperature for Lodwar in Turkana County, Kenya. Temperature and rainfall data used was for the period 1979 to 2012 and 1950 to 2012, respectively. The results revealed a slight decreasing (increasing) trend in the MAM (OND) seasonal rainfall. However, none of the trends was statistically significant. Maximum and minimum temperatures depicted statistically significant increasing trends at seasonal scales.

In the recent years, trend analyses of rainfall and temperature patterns in Machakos County have been carried out (Njiru *et al*., 2010; Omoyo *et al*., 2015).

Omoyo *et al*. (2015) evaluated the effects of climate variability on maize grain yield in Machakos, Kitui, Mwingi and Makueni Counties for the period 1979 to 2009. In Katumani, Machakos County, the results showed insignificant decreasing trends in the seasonal and annual rainfall over the study period, whereas maximum and minimum temperature patterns exhibited warming trends at both seasonal and annual scales. Both MAM and OND seasonal rainfall exhibited high variability (CV > 30%). It was also noted that the onsets were highly variable (CV= 98.1%).

Njiru *et al*. (2010) analysed climate data and its associated risks on maize production in the semi-arid eastern Kenya. Katumani and Kambi ya Mawe in Machakos and Makueni Counties, respectively were selected as the study areas. Rainfall and temperature data for Katumani meteorological station was for the period 1957 to 2008 and 1986 to 2008, respectively, whereas, for Kambi ya Mawe rainfall and temperature data was from 1959 to 2008 and from 1971 to 2008, respectively. They observed high variability in the short rains (OND). The results also depicted a decline in both the seasonal and annual rainfall totals. Increasing trends in both maximum and minimum temperatures were revealed.

However, such studies did not present comprehensive information on the variability and trends of the intra-seasonal rainfall characteristics within the county. Omoyo *et al*. (2015) only considered the onset, cessation dates and seasonal rainfall amounts in their study. Understanding the variability and trends of most of the intra-seasonal rainfall characteristics (duration, number of rainy days and frequency of dry spells etc) is important because it has a repercussion on the distribution of water within a growing season which finally affects crop yields.

In addition, none of the studies within Machakos County considered the non-parametric methods such as Mann-Kendall test to analyze the temporal trends. Although the non- parametric methods are less powerful compared to parametric methods, they don't require the data to be normally distributed, they are insensitive to outliers (Shadmani *et al.*, 2012). Relevant reviews on trend analysis of climate parameters using Mann-Kendall test include Modarress and Silva 2007; Boroujerdy 2008; Tabari *et al*., 2011; Mondal *et al*., 2012; Wagesho *et al.*, 2013; Gitau *et al*.,2018.

2.3 General Information and Agronomic Features of Sorghum

2.3.1 Origin and Distribution of Sorghum

It is known that sorghum originated in Ethiopia between 5000 and 7000 years ago (ICRISAT, 2005). From Ethiopia it was spread throughout Africa and Asia continents (Dicko *et al*., 2006). In the 1700-1800's sorghum was introduced to North America from West Africa through the slave trade and was later re-introduced in Africa in the late 19th century as a cash crop and spread to South America and Australia. Currently sorghum is extensively cultivated in the dry areas of eastern and southern Africa, Asia (India and China), America and Australia where rainfall amounts are too low to support maize production (Dicko *et al*., 2006; Demeke and Marcantonio, 2013).

2.3.2 Classification of Sorghum

Sorghum belongs to the genus *Sorghum Moench,* family *Poacea,* subfamily of *Panicoideae*, tribe *Andopogoneae*, and sub-tribe *Sorghinae* (Leonard and Martin, 1963; Dahlberg, 2000). It is generally described as an annual, vigorous, coarse, erect cane like grass of height ranging from 0.5 to 6m tall. Variability in its growth characteristics is attributed on the genotype and growing conditions (Purseglove, 1972).

It has been known to be drought tolerant crop (Khosla *et al*., 1995). This has been attributed to the following four features (i) its root to leaf surface area is very large; (ii) rolling of the leaves to reduce the rate of transpiration during drought episodes; (iii) if drought extends for longer periods, rather than drying it will go in to dormancy; and (iv) its leaves have a waxy cuticle which protect them (Khosla *et al*., 1995).

Over the years, research institutions including Kenya Agricultural & Livestock Research Organization (KALRO) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have developed and released a number of sorghum cultivars. The most common cultivars include Serena, KARI Mtama 1, Seredo and Gadam (Table 2 and Figure 2) (KALRO, 2006; Miano *et al*., 2010).

Table 2: Sorghum cultivars grown in Kenya and their characteristics

	Characteristics					
Cultivar	***Plant height (cm)***	***Flowering (days)***	***Maturity (days)***	***Grain colour***	***Potential yield (kg/ha)***	***Tolerance***
Serena	150-160	69-78	110-120	Brown	1800-2300	Striga, drought
Kari Mtama 1	50-170	58-65	95-100	White	1800-4000	Drought
Seredo	150-160	65-77	110-120	Brown	4000	Drought
Gadam	100-130	45-52	85-95	Grey	1700-4500	Pests, leaf diseases, low rainfall

(Source: KALRO, 2006)

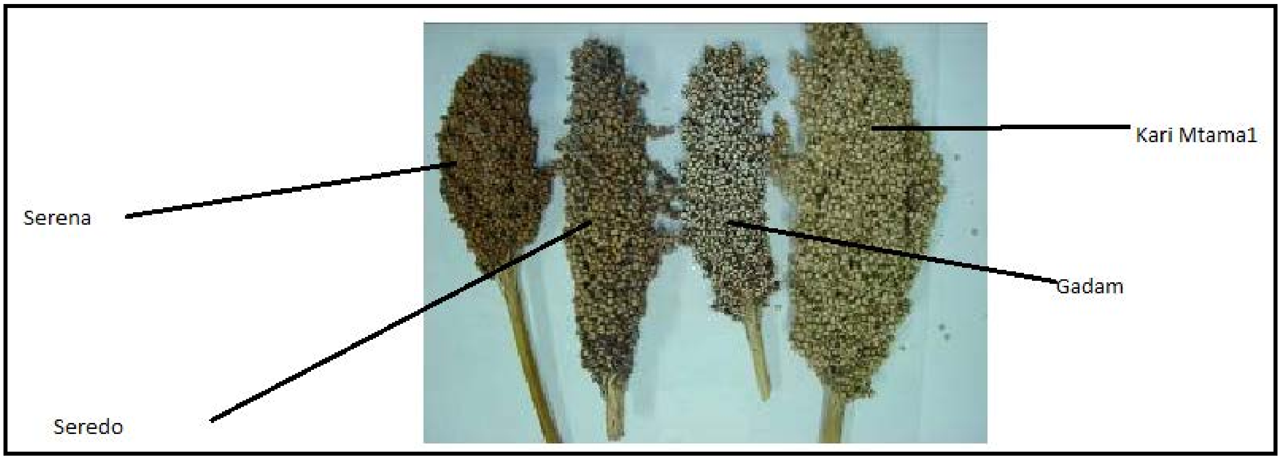

Figure 2: Sorghum panicles of the four major common sorghum cultivars in Kenya, (source: KALRO, 2006)

KALRO in 2009 introduced a new sorghum variety “Gadam” in semi-arid Eastern Kenya so that farmers can enhance their food security, income and alleviate poverty (Anon, 2010). This early maturing and high yielding cultivar has managed to flourish in harsh environments and has become very important to smallholder farmers in the same region (Karanja *et al.*, 2006). Gadam sorghum is appropriate for malting purposes because of the high and low content in starch and protein, respectively. Compared to maize and barley whose carbohydrates content is 66% and 67%, Gadam has 75% carbohydrate making it an excellent substitute source of starch (Esipisu, 2011). In 2010, the demand for Gadam sorghum was estimated by KALRO to be approximately 60,000 tonnes owing to the increased demand from East African Breweries Limited (EABL).

Compared to other sorghum cultivars and maize cultivars, Gadam matures earlier making it the perfect cultivar for regions receiving erratic and low rainfall. In Machakos, the cultivar has been reported to exist and produce grain with seasonal rainfall amount of approximately 200 mm (Miano *et al*., 2010). The Seredo variety out yields Serena by approximately 10%. Seredo is drought resistant and suitable for altitudes below 1500m and matures slightly later than Serena. Plants are short, semi- erect with medium sized, vertical and very dense ear heads. Its panicles are compacted and brown in colour. The grains are bit larger and heavier than Serena.

2.3.3 Sorghum Growth and Development Stages

Grain sorghum has nine different development stages from emergence to maturity (Vanderlip, 1993) (Figure 3). These development stages can be further grouped in to three growth stages.

Table 3, gives an outline of the growth and development stages of sorghum. The duration of each of the stages and its impact on yield and yield components is attributed to the environmental factors (water, climatic conditions, soil fertility), planting dates, management practices, hybrids; and variability of these factors may be yearly and from one location to another.

Table 3: Grain sorghum growth stages, approximate time interval between the different growth stages and the identifying characteristics

Growth Stage	**Development Stage**	**DAE(Days After Emergence)**	**Visual Characteristics**
Growth Stage1 (Vegetative Phase)	**0**	0	Emergence: plant visible at soil surface
	1	5	Collar of 3rd leaf visible
	2	10-15	Collar of 5th leaf visible
	3	25-30	Growing point differentiation or panicle initiation (approximately 8th leaf visible).
Growth Stage 2 (Reproductive Phase)	**4**	35-40	Elongated stem and increases in leaf area ,the final leaf, (flag leaf) is visible in the whorl
	5	40-55	Booting; attainment of maximum leaf area; potential panicle size has been determined.
	6	55-65	Flowering (bloom); 50% of plants in the field have flowered
Growth Stage 3 (Grain Filling Phase)	**7**	65-80	Soft dough; Formation of grain commences immediately after flowering and the grain filling is rapid (50% of dry weight). Grain are easily squeezed between the fingers, the stem begins to lose weight due to a remobilization process
	8	80-90	Hard dough; Grain has accumulated 75% of its dry weight; uptake of nutrients is almost complete. Functionality of the lower leaves is lost owing to senescence or remobilization of nutrients to grains
	9	90-110	Physiological maturity; Maximum grain dry weight has been attained; dark spot (black layer) at the base of the kernel determines maturity of the grain; moisture levels in the grain ranges from 25% to 35%; harvesting depends on the environmental conditions.

Source: Prasad and Staggenborg, 2009

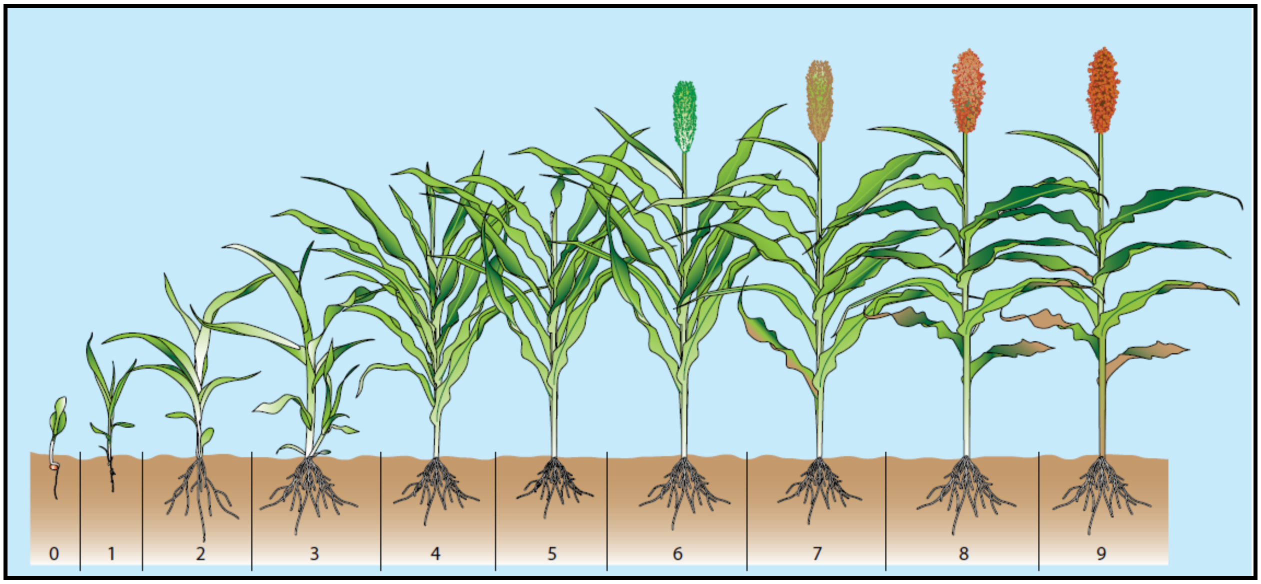

Figure 3: Sorghum growth stages from emergence to maturity according to Vanderlip (1993).

2.3.4 Climate Conditions, Soil and Water Management

Optimum temperature for sorghum growth is generally between 26°C to 34°C, but this is dependent on the plant growth stage (Peacock and Heinrich, 1984). The mean optimum temperature range for seed germination, vegetative growth, and reproductive growth for sorghum is 21°C to 35°C, 26°C to 34°C and 25°C to 28°C, respectively (Maiti, 1996).

The crop performs well in regions having an annual rainfall range of 325 to 425mm (Balasubramaniyan and Palaniappan, 2004). Water use efficiency in sorghum is largely dependent on environmental conditions and the growth stages of the crop. During the vegetative phase less water is required (1 to 2.5 mm/day), this sufficient to evade water stress. The rate of transpiration in young plants is lower because the leaf surface area is smaller. The water use during reproductive phase is maximum (approximately 7 to 10 mm/day) owing to higher rates of transpiration due to larger leaf surface area. As the plants approaches maturity, the overall water requirement starts declining slowly due lesser evaporative demand, reduced transpiration rates owing to leaf senesce and modification in plant physiology. During grain filling phase, water is mainly intended for grain production (Stichler and Fipps, 2003).

Sorghum is mainly grown on many different soils, ranging from high clay content to low sand content (Donaldson, 2001), which are usually not suitable for production of maize. Best growth is attained on loam and sandy soils. The crop can adapt well to soils with pH between 5.5 and 8.5 (Clark, 1982). However, it grows well in soils with pH values ranging from 6.2 to 7.8 (Cothren *et al.,* 2000). The attribution being that it is the pH range at which majority of the nutrients are more easily reachable to plant roots.

In more acidic soils (pH below 5.5) Phosphorus, which is one of the macronutrients may be lacking in the soils. In many alkaline soils (pH above 7.8) some of the micronutrients may become limited, but in sorghum fields these deficiencies are hardly ever seen (Espinazo and Kelley, 2005).

2.3.5 Importance of Sorghum

Sorghum is the third most important cereal crop grown in Kenya (GoK, 2002; AGRA, 2013; MoA, 2013). Sorghum is used as human food, feed for animals and raw material for industries (Mamoudou *et al*., 2006). The crop is an important cereal crop and staple food of more than 0.5 billion people in more than 30 developing countries (Kumar *et al*., 2011).

The nutritive value of sorghum grain is high, with 70-80%, 11-13%, 2-5%, 1-3% and 1-2% carbohydrate, protein, fat, fiber, and ash, respectively (Prasad and Staggenborg, 2009), hence it forms important part of the diets of many people in the world as it may be utilized to diminish malnutrition brought about by micronutrient. In Africa sorghum plays double role in farmers' lives by providing income and ensuring food security (Anglani, 1998). In industries, the grain is used to produce syrup, wax, starch, distilled and undistilled beverages, edible oils, dextrose agar, and gluten feed (Rainford, 2005; Mamoudou *et al*., 2006). As food, the grain is used in preparing porridge, pilau, ugali and customary dishes when mixed with legumes (Ministry of Agriculture, 2010). Eco-friendly packaging materials, wallboard, fences and solvents can be made from sorghum fibers. Dried sorghum stalks can be utilized as cooking fuel and animal feed (Maunder, 2006). Despite the high demand for sorghum by the brewing industries to substitute barley, the quantity produced by farmers continues to be low and unable to satisfy the demand.

2.3.6 Sorghum Productivity

Sorghum productivity varies across the different parts of the world. Average yield is 1.3t/ha, 3.1t/ha and 1.1 t/ha from the world, developed countries and developing countries. The estimated average grain yield of sorghum in Kenya is 0.8t/ha (FAO, 2012). The yield is low because cultivation of sorghum is largely characterized by traditional agricultural practices; with low farm inputs (no application of inorganic fertilizer or pesticides), no improved agronomic practices and use of traditional varieties (Taylor, 2012). In order to sustain higher yields, the key agronomic operations for sorghum must be practiced, plant population density and the soil nutrient status have to be maintained through application of suitable rates of nitrogen and phosphorus fertilizer (Weltz *et al*., 1998).

2.3.6.1 Key Agronomic Operations of Sorghum

For quick germination, sorghum should be planted in soils which are warm, moist, supplied with enough air and sufficiently fine so as to offer good contact between the soil and the seed. The most essential agronomic practices which have significant influence on sorghum production include: cultivation, application of both organic and inorganic, seeding rates, planting time, planting depth, disease, and weed management. In the area of study, sorghum is mostly produced under rain-fed conditions. Plant populations vary depending on rainfall and growing conditions. High (low) plant populations' supports fewer (more) tillers and are essential in higher (lower) rainfall areas (Shroyer *et al*., 1998).

Proper planting time is needed so that flowering of the crop does not coincide with the dry periods. Planting too early before the rainfall onsets results in delayed emergence and reduced plant stands. On the other hand, late planting may not allow the crop to mature. The optimal planting depth varies depending on the soil types and moisture conditions. A planting depth of 25mm is adequate in soils which are heavier. However in sandy soils, seeds can be sown at a depth of 50mm (Shroyer *et al*., 1998). For farmers to improve water use efficiency and yield at the lowest possible cost, it is important that soil fertility management based on soil test results be taken into consideration (McClure, 2013). Application of either organic or inorganic fertilizers or consideration of prior crops and of soil test values may help in managing the nutrients in the soil (Wortmann *et al.,* 2013).

The farmers should be able to identify the diseases that often occur in their growing environment (Lance, 2013). The use of varieties which are disease-resistant and employing good agricultural practices helps in managing sorghum diseases. Occasionally the proper use of pesticides plays a important role in managing certain diseases in sorghum (Buntin, 2012).

Sorghum grain attains physiological maturity when the moisture in the grain is approximately 25-35%. In order to reduce harvest losses and drying expenses the crop should be harvested when the moisture content in the grain is about 20%. However if the sorghum is to be stored for longer periods (>12 months), the crop should be dried until the moisture content is less than 12% (Sumner, 2012). It is important to identify a safe storage environment so as to protect the crop from damage by insects, molds, and rodents and the consequently the financial loss that can result (McNeill and Montross, 2003).

2.3.6.2 Response of Sorghum to Inorganic Fertilizer

Depleted soil nutrients are one of the bottlenecks for sustaining agricultural productivity in Kenya. Improvement of soil fertility has been known to be the basic prerequisite to attain lasting food security and improve living standards of smallholder farmers (IFPRI, 2010; Jensen *et al.*, 2012). Fertilizer use constitutes an essential part of improved soil fertility and thus improved crop production. It has been renowned that proper amount and timing of fertilizer application is the key to bumper crop production (Sharma *et al.*, 1996; Tariq *et al.*, 2007). In any farming system the use of inorganic fertilizers is vital as they provide the essential nutrients in forms readily available for uptake by plants. The growth, development and yield of any crop can be negatively affected by limited or too much supply of any one of essential nutrients.

The vital elements limiting plant growth and development are nitrogen (N) and phosphorous (P). These nutrients in the soil become depleted with time due to erosion of soil, leaching of nitrogen, phosphorous fixation, and removal by crops (Oldeman *et al*., 1991; Jarvis, 1996; Zobeck *et al*., 2000, Holmgren and Scheffer, 2001). In Kenya, there has been a steady exhaustion of soil nutrients mainly because of limited utilization of both organic and inorganic fertilizers. This has been the main reason of low soil fertility in the country (Smaling *et al*., 1997). In 1990, the average fertilizer use in the developing countries especially those in the Asian continent was 81 kg/ha. This was very high compared to Kenya, where the average fertilizer use was barely 9.4 kg/ha (Ogola *et al*., 2002).

Current data indicate that Kenya has expanded fertilizer usage to 30 kg/ha and is anticipated to increase to 50 kg/ha by 2015 (Mwangi, 2011). To sustain high levels of crop production, the soil nutrient status has to be maintained through practicing crop rotation and the use of organic and inorganic fertilizers (Weltz *et al.*, 1998).

Nitrogen is the most important nutrient essential for high grain sorghum productivity. To obtain sorghum yield of 3.5 t/ha, 5.2t/ha and 6t/ha, nitrogen should be applied at 85, 130 and 150 kg of N/ha, respectively (Eweis *et al.*, 1998). Exposing sorghum plant to stress of nitrogen at any phase of its life cycle might lead to detrimental effects on growth, yield and its components.

Saaka *et al*. (2012) determined the agronomic benefits of applying nitrogen, phosphorus and potassium fertilizers to sorghum in Guinea savanna of Ghana. Four levels of nitrogen (0, 40, 80, and 120 kg N ha^{-1}) were combined with two P levels (0 and 17.2 kg P ha^{-1}) and two K levels (0 and 33.3 kg K ha^{-1}). Source of N, P and K was urea, triple superphosphate and muriate of potash, respectively. The experiment was randomized complete block design (RCBD) with three replications. Across the years it was deduced that additional potassium fertilizer did not have any influence on the sorghum components and its yield. Nevertheless, application of phosphorus fertilizer increased yield by 14%, and sorghum yield increased by 47%, 60% and 69% as result of application of 40, 80, and 120 kg N ha^{-1}.

Alemu and Bayo (2005) determined the effects of combined nitrogen and phosphorus fertilizer on sorghum in North Eastern, Ethiopia. They reported that sorghum grain yield increased from 0.54 tons ha^{-1} in the control (no fertilizer) to 3.77 tons ha^{-1} with the application of 120 kg ha^{-1} N and 60 kg ha^{-1} P, respectively. Yields were also significantly different with the interaction of 0, 30 and 60 kgha^{-1} P at all levels of N except with 0 kgha^{-1} N.

Hassan *et al*. (2011) investigated the effects of N and P inorganic fertilizer application rates on the growth and yield of sorghum in the vertisol soils of Southern Gedarif. Four N levels (0, 21.5, 43, and 64.5 Kgha^{-1}) were applied at sowing while four P levels (0, 21.5, 43, and 64.5 kgha^{-1}) during top dressing. Highest grain yield of 1977 kgha^{-1}were attained by the interaction of 43 kgha^{-1} N and 64.5 kgha^{-1} P.

Kayuki *et al*. (2012) explored the response of sorghum to fertilizer application in the semi arid parts of Uganda. Mean sorghum yield with zero nitrogen application (N_0) was 0.69 Mg ha^{-1} and this was constantly increased by a mean of 230% with nitrogen application. Sorghum did not respond to potassium (K) fertilizer application. Aboveground biomass increased from 31.3 kg ha^{-1} to 75.9 kg ha^{-1} with 0 and 90 kg ha^{-1} N application, respectively.

Ashiano *et al*. (2005) examined the effect of Nitrogen (N) and Phosphorus (P) application rates on the growth and yield of dual-purpose sorghum in Lanet, Kenya. Five N levels (0, 20, 30, 40 and 50 kgha^{-1}) were combined with five P levels (0, 20, 30, 40 and 50 kgha^{-1}). The results showed that N and P levels beyond 40 and 30 kgha^{-1}, respectively, did not increase plant height, seed weight and grain yield.

2.3.6.3 Response of Sorghum to Plant Population

Plant population is a variable that can significantly affect sorghum production. Optimum plant spacing depends on availability of moisture and soil type. At higher plant population density sorghum plants have a tendency to flower earlier, grow taller and produce larger leaf compared to those at lower plant population densities (Buah and Mwinkaara, 2009). Moreover, late flowering in low plant population imply that development of the crop and harvesting may be delayed (Kinry *et al*., 1998). Greater competition for light in higher plant population may result to increased plant height. Low plant population (wider row spacing) may result to low yield due to lesser crop stand as compared to high plant population (narrow spacing). Reducing the intra row spacing can also assist in weed control by increasing crop competitiveness for light and hence less light is transmitted to the soil and thus increases in sorghum grain yield resulting from higher plant populations (Coulter, 2009).

Schatz *et al*. (1990) investigated the effect of plant density on grain sorghum production in North Dakota. They reported that low plant population (30,000 plants ha^{-1}) produced a total of 79,000 panicles, while that of high plant population (90,000 plants ha^{-1}) produced 111,000 panicles. This increase in the number of productive panicles per hectare clarifies the increased grain yield of sorghum at the higher plant population.

Zand *et al.* (2014) investigated the response of sorghum to nitrogen fertilizer at different plant densities in Iran. The results revealed that increase in nitrogen application rates and plant population led to an increase in both biomass and sorghum grain yield.

Mekdad and Rady (2016) examined the response of sorghum varieties to plant density in Egypt. The results showed that the days to 50% flowering and grain yields increased with increase in plant density.

Generally the recommended spacing for sorghum in Kenya is 75 cm by 20 cm between rows and plants, respectively (MoA, 2012).

2.4 An Overview of Agricultural Production Systems sIMulator Model

Crop models are programs generated by a computer and assimilate information on daily weather, genetics, pests, management and soil characteristics to predict main processes associated with the growth and development of the crop including the final harvestable biomass and yield (Jame and Cutforth, 1996; Batchelor, 1999).

There are several crop growth models; the choice of an appropriate model depends on the complexity of the model and its appropriateness to the problem being investigated, whether the model has been tested in diverse environments and the availability of input data (Travasso *et al.*, 2006).

Amongst the various crop growth models, the current study employed the use of Agricultural Production Systems sIMulator (APSIM) model version 7.8 because of various reasons but not limiting to the following; the complexity of the APSIM model is medium and input data requirements is medium. APSIM model operates on a daily time step and uses different component modules to simulate cropping systems. These modules are linked via the APSIM engine and can be illustrated by a spider diagram (Figure 4) (McCown *et al.*, 1996; Keating *et al.*, 2003; van Ittersum *et al.*, 2003). The modules can be classified in three broad categories as: biophysical, environmental or soil and managerial or economic.

The biophysical modules in APSIM simulate the biological and physical processes in any farming systems. It is comprised of various crop modules (Table 4). The biophysical modules use a simplified structure to illustrate the daily capture and use of climate parameters, soil water and soil nutrients. Plants will then develop through various distinctive phenological phases in reaction to environmental stimuli (Keating *et al*., 2003).

The soil modules include residues, surface organic matter, manure, soil phosphorus (SOILP), soil water (SoilWAT) and soil nitrogen (SoilN) modules (Table 4). SoilP module specifies phosphorus supply in the soil; soilN illustrates the dynamics of both nitrogen and carbon in the soil and also their transformation which are considered on individual layers. The soilWAT deals with characteristics of water in each layer of the soil such as saturated volumetric water (SAT), wilting point (LL15) and drained upper limit (DUL) among others (Keating *et al*., 2003; Kirschbaum *et al*., 2001).

There is a user defined script language within the management module which controls the module. The module allows users to specify particular management operations (Table 4). The management operations can be date of sowing, tillage, residue management, harvesting among others (McCown *et al*., 1996; Keating *et al*, 2003).

Long-term climate data for particular meteorological stations are contained within the “met" module. In addition the climate control module gives a window for inserting magnitudes of projected mean changes of climate parameters (rainfall, maximum and minimum temperature, solar radiation and CO_2). Detailed information on the modules and several others are outlined by Keating *et al*. (2003).

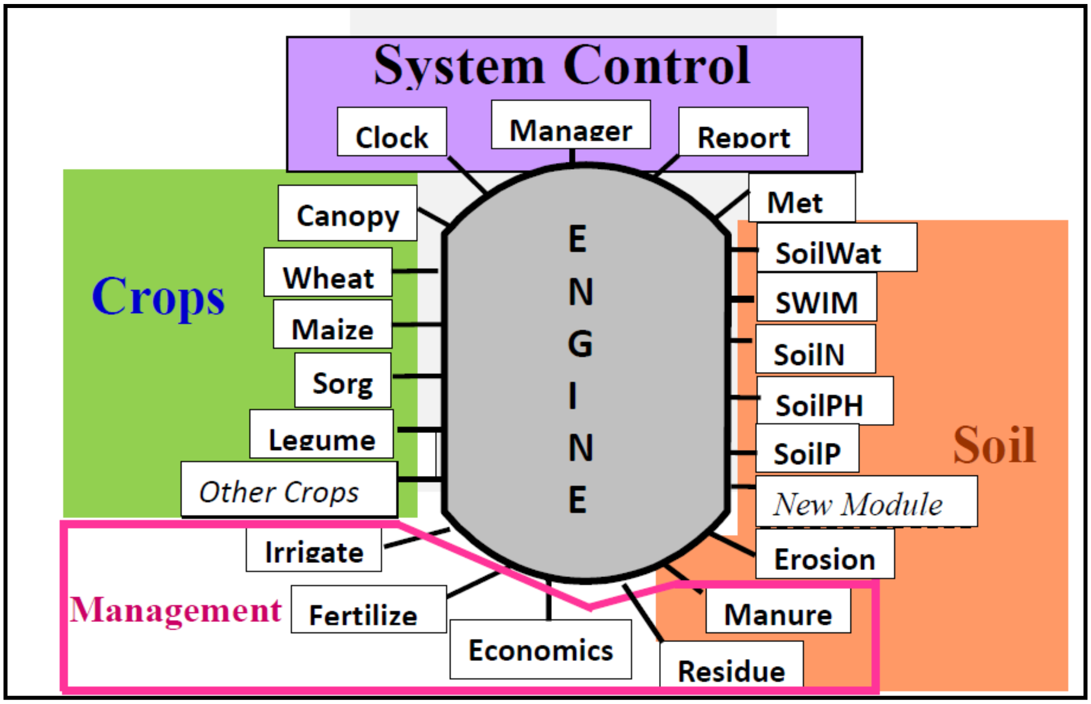

Figure 4: APSIM Modeling Framework (source: Keating *et al*., 2003)

Table 4: Most important modules in APSIM

Model type	**Module name**
Biological	Barley, canola, chickpea, cotton, cowpea, fababean, hemp, lucerne, maize, millet, mungbean, native pasture, navybean, peanut, pigeonpea, sorghum, soyabean, stylo pasture, sunflower, wheat
Environmental	erosion, manure, residue, solutes, soilP, soil pH, soilN, soilWat, SWIM
Management	accumulate, canopy, clock, fertilizer, input, irrigate, manager, met, micromet, operations, report,

Source: Adapted from Jones et al., 2001

2.5 Global Climate Models and Assessment of their Skills

2.5.1 Global Climate Models

Climate models are computer driven programs used for simulating both the current climate and projecting future climate changes under different scenarios brought about by emissions of greenhouse gases (Jiang *et al.*, 2011). Table 5 shows the CMIP5 GCMs that have been used within Coordinated Regional Downscaling Experiment (CORDEX). The development of the Coupled Model Intercomparison Project (CMIP) was encouraged by World Climate Research Program (WRCP).

The CMIP5 GCMs simulations are downscaled for the entire African domain at a spatial resolution of 0.44° (50km) using the newest version of the Rossby Centre Regional Climate Model (RCA4). The 8 GCMs run in transient mode for the period 1951 to 2100 (1951 to 2005 for historical period and 2006-2100 for scenarios) and sample both RCP4.5 and RCP8.5.

Table 5: Coupled Model Intercomparison Project Phase 5 Global Climate Models used within CORDEX

S/No.	***Institute Name***	***Country***	***GCM Name***	***Calendar***
1.	Canadian Centre for Climate Modelling and Analysis (CCCma)	Canada	CanESM2	365 days
2.	Centre National de Recherches Meteorologiques (CNRM-CERFACS)	France	CNRM-CM5	Standard
3.	Met Office Hadley Centre (MOHC)	UK	HadGEM2-ES	360 days
4.	Norwegian Climate Centre (NCC)	Norway	NorESM1-M	365 days
5.	Irish Centre for High-End Computing (ICHEC)	Europe	EC-EARTH	Standard
6.	Model for Interdisciplinary Research on Climate (MIROC)	Japan	MIROC5	365 days
7.	National Oceanic and Atmospheric Administration-Global Fluid Dynamic Laboratory (NOAA-GFDL)	USA	GFDL-ESM2M	365 days
8.	Max Planck Institute for Meteorology (MPI-M)	Germany	MPI-ESM-LR	Standard

(Source: http://pcmdi9.llnl.gov/)

Note that HadGEM2-ES has the 360 days calendar meaning all the months have 30 days. The models with 365 days indicate that the model has all Februarys with 28 days, irrespective of the leap years. Standard calendar means that the years with leap years have been accounted for.

2.5.2 Climate Change Emission Scenarios

The use of scenarios of climate change has been at the center of evaluations of climate change effects or impacts on agricultural and water resources (Rosenberg, 1992). The study was based on latest set of scenarios which replaced the Special Report on Emissions Scenarios (SRES) standards (IPCC fifth assessment report (AR5) that was released in 2014). These scenarios are known as the Representative Concentration Pathways (RCPs) and thir naming is dictated by the radiative forcing target level by the year 2100. The estimations from the radiative forcing are established on the greenhouse gases (GHGs) forcing and other forcing agents. There are four selected RCPs: RCP2.6 (mitigation scenario), RCP4.5 and RCP6 (medium stabilization scenarios and RCP8.5 (very high baseline emission scenarios). More details on these RCPs are discussed in the following subsections.

2.5.2.1 RCP8.5

RCP8.5 was developed using the Model for Energy Supply Strategy Alternatives and their General Environmental impacts (MESSAGE) model and the International Institute for Applied Systems Analysis (IIASA) Integrated Assessment Framework in Austria. This RCP is described by rising amounts of GHGs emissions over time as a result of projections of increased human population of 12 billion by the year 2100, highest rates of urbanization and inadequate rates of technological change (Riahi *et al.* 2007), hence it is a high emission scenario.

2.5.2.2 RCP6

RCP6 was developed in Japan by the Asian Pacific Integrated Model (AIM) modeling team at the National Institute for Environmental Studies (NIES). It is an intermediate stabilization scenario in which total radiative forcing becomes stable shortly after 2100. The stabilization is attributed to the application of an array of technologies and policies for reducing the emission of GHGs (Fujino *et al.,* 2006; Hijioka *et al*., 2008).

2.5.2.3 RCP4.5

RCP4.5 was developed in the United States at the Pacific Northwest National Laboratory’s Joint Global Change Research Institute (JGCRI) by the Global Change Assessment Model (GCAM) modeling team. It is also a medium stabilization scenario in which total radiative forcing is stabilized shortly after 2100 (Smith and Wigley 2006; Clarke *et al*. 2007; Wise *et al.* 2009). Stabilization is attributed to lower rate of increasing human population as compared to RCP8.5 and intermediary levels of economic growth.

2.5.2.4 RCP2.6

RCP2.6 was developed by the Integrated Model to Assess the Global Environment (IMAGE) modeling team of the PBL Netherlands Environmental Assessment Agency. It is a low emission scenario whereby it is assumed that the concentration levels of GHGs in the atmosphere will be significantly reduced ultimately (Van Vuuren *et al.* 2007). Table 6 shows an overview of the Representative Concentration Pathways. However, one medium stabilization scenario (RCP4.5) and high emission scenario (RCP8.5) were used in the current study.

Table 6: An overview of the Representative Concentration Pathways

Name	***Description***	**CO_2 Equivalent**	***SRES equivalent***	***Integrated Assessment Model (IAM)***	***Publication***
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 by 2100	~1370ppm	A1F1	MESSAGE	Riahi *et al*., 2007
RCP6	Stabilization without overshoot pathway to $6W/m^2$ at stabilization after 2100	~850ppm	B2	AIM	Fujino *et al*., 2006; Hijioka *et al*., 2008
RCP4.5	Stabilization without overshoot pathway to $4.5W/m^2$ at stabilization after 2100	~650ppm	B1	GCAM	Clarke *et al*., 2007; Smith and Wigley 2006; Wise *et al*.,2009
RCP2.6	Peak in radiative forcing at $\sim3W/m^2$ before 2100 and then decline(the selected pathway declines to $2.6W/m^2$ by 2100)	~490ppm	NONE	IMAGE	vanVuuren *et al*.,2007; van Vuuren *et al*.,2006

(Adapted from van Vuuren *et al.,* 2011)

2.5.3 Measures of Skill

Confidence in any climate model depends on its skill to replicate vital features of the present and past climates. In general combining different models enhances the skill, reliability and consistency of model predictions. Over the past years, a number of measures of skill of climate models have been developed (Kittel *et al.,* 1998; Sun *et al.*, 1999; Murphy *et al.*, 2004; Johns *et al*., 2006; Shukla *et al*., 2006; Min and Hense, 2006; Nieto and Puebla, 2006; Anyah *et al*., 2006; Perkins *et al.*, 2007; Maxino *et al*., 2008; Mwangi , 2010; Masanganise *et al*., 2013; Bosire *et al*., 2014). These studies evaluated the performance of both individual and multi-model ensembles of GCMs using daily, monthly or annual time-scale data of climate variables. Nevertheless, there has been no standard approach of assessing the skill of GCMs.

Kittel *et al.* (1998) compared the outputs from 9 GCMs and observed data from seven sub-continental areas (Central North America, Southern Asia, Sahel, Southern Europe, Australia, Northern Europe and Eastern Asia) using bias. Their results demonstrated that two GCMs (CSIRO Mk2 and HadCM2) simulated both rainfall and temperature relatively well.

Murphy *et al.* (2004) used climate prediction index (CPI) to assess the confidence of a model using a wide range of climate variables. A low index values denotes "good", thus models with lower values of CPI the higher its reliability in the prediction of the future climate. The index was also used by Johns *et al*. (2006) using dissimilar variables from those used by Murphy *et al.* (2004).

Min and Hense (2006) evaluated the performance of GCMs using Bayesian approach. The approach is based on Bayes factor or likelihood ratio, which are used as weighting factors to produce the Bayesian model averaging (BMA) which incorporates skills of each model. They concluded that averaging the skills of individual models using Bayes factors is more useful than moments estimated by conservative statistics.

Shukla *et al*. (2006) assessed the performance of 13 climate models using relative entropy (difference between two probability distributions) for surface air temperature during the past 100 years. The lower the value of relative entropy the closer the model's distribution is to the observed data and the higher the sensitivity of the model to doubling of the concentration of CO_2. They found out that models displaying higher reliability in simulating the present climate generated more distinct global warming.

Nieto and Puebla (2006) assessed the performance of nine (9) climate models in simulating rainfall over the Iberian Peninsula using spectral analyses and empirical orthogonal functions. Two models (MRI and GFDL) were able to replicate observed rainfall during winter.

Perkins *et al.* (2007) assessed the performance of the climate models within the IPCC AR4 in simulating daily rainfall, maximum and minimum temperature over Australia using probability density functions (PDFs). Three models (CSIRO, ECHO-G and MIROC-M) were found to be more skilful over the region, hence they were recommended for use in the assessments of impact of climate change.

Maxino *et al*. (2008) used probability density functions to characterize the skill of the IPCC AR4 models in simulating rainfall, maximum and minimum temperatures over the Murray-Darling Basin in Australia. Three models (CSIRO, IPSL, and MIROC-M) matched the observed PDFs of the three climate variables relatively well.

Masanganise *et al.* (2013) assessed the performance of five (5) GCMs in predicting rainfall and temperature in Zimbabwe using coefficient of determination, model efficiency and root mean square error. The results indicated that the predicted temperature showed higher agreements with the observed temperature. Thus, there is more confidence in simulated temperature than rainfall. Amongst the 5 GCMs, the CGCM3 model performed better in replicating the observed fields.

Anyah *et al*. (2006) investigated the variability of climate in the Greater Horn of Africa using NCAR-GCM ensemble. The model was able to fairly reproduce rainfall variability over different homogeneous climate sub regions in East Africa, with the exception of the central highlands and northeastern parts of Kenya.

Mwangi (2010) assessed the skill of ECHAM 4.5 in simulating rainfall on seasonal time scales (MAM and OND) over the Grater Horn of Africa (GHA) region for the period 1961to 2008. Methods used were RMSE and correlation coefficients. Larger correlation coefficients and smaller values of RMSE were noted within the equatorial sector. The model was able to replicate the observed data fairly well during the OND season as compared to the MAM season.

Sun *et al*. (1999) used the NCAR Regional Climate Model to predict the rains over Eastern Africa during autumn season. The model was able to reproduce the climatological rainfall pattern over the East Africa when compared to observations. There was also a good agreement between the month-to-month variations of the simulated rainfall and the observed data. This demonstrated the skill of NCAR-RegCM2 model to represent the monthly rainfall pattern over East Africa domain.

Bosire *et al*. (2014) assessed the skill of climate forecast system model in predicting seasonal rainfall (MAM and OND) over East Africa region using categorical skill scores. The results established relatively higher skills in simulating OND seasonal rainfall compared to MAM seasonal rainfall.

2.6 Previous Studies Using APSIM

In recent times, many researchers have used APSIM model to investigate the impacts of fertilizer use and climate change on crop growth and development.

Chen *et al*. (2010) analyzed the response of maize and wheat productivity in the North China Plain using APSIM model. A double cropping system was applied in the study. Root mean square error was used to compare the simulated and observed yield and biomass for both maize and wheat. The values obtained were 1.07 and 1.70 t ha^{-1} for maize and 0.83 and 1.40 t ha^{-1} for wheat, respectively.

Kpongor (2007) used APSIM-Sorghum model version 4.0 to simulate the response of biomass and yield of sorghum to nitrogen and phosphorus inorganic fertilizer in Ghana. The model was able to replicate the observed biomass and grain yield of sorghum with an average coefficient of determination (R^2) of 86% and 81%, respectively.

Mc Carthy and Vlek (2012) evaluated the potential impact of climate change on sorghum grain yield under different nutrient (0, 30 and 40 kg P ha^{-1}) management systems in a smallholder farming system using APSIM in Ghana. Sorghum grain yield was projected to decline by 20% with no fertilizer application (0 kg P ha^{-1}). However, with the application of fertilizer (30 and 40 kg P ha^{-1}) sorghum grain yield increased by 4%.

Fosu Mensah (2013) parameterized and evaluated APSIM model in response to maize productivity in sub humid Ghana. The evaluation results revealed that APSIM was able simulate maize grain yields better with a coefficient of determination (R^2) of 0.88 and 0.90 for the two maize cultivars Dorke and Obatanpa, respectively.

Dimes and Du Toit (2009) utilized the APSIM model to simulate the yields of cowpea, groundnut and maize and also the crops' water balance in the growing season of the year 2007/2008 in the Limpopo Province. It was noted that simulation of maize yields using APSIM was better. However, there was a slight under- prediction of biomass of the groundnut and cow pea. The reliability of using APSIM to simulate changes in soil water was also higher in maize as compared to groundnut and cowpea.

Delve *et al*. (2009) used APSIM-model to predict responses of phosphorus in maize and beans on contrasting soil types (Oxisol and Andisol) in Kenya. APSIM was capable of replicate the observed observed biomass and grain yield of maize with a coefficient of determination of 88% and 81%, respectively on Oxisol and 83% and 74%, respectively on Andisol. Mean coefficient of determination of 69% and 79% was reported for biomass and grain of beans. They concluded that the APSIM model predicted the growth of maize and beans reasonably well for the different rates of phosphorus and treatments.

2.7 Climate Change and Sorghum Production

Reilly *et al.* (2001) investigated the probable impacts of climate variability and change on agriculture for the United States. They used scenarios obtained from two GCMs (Canadian Climate Centre (CCC) and United Kingdom Meteorology Office (UKMO)). Under the CCC scenario, they predicted 17% increase in sorghum yields by 2030 even though precipitation is expected to decrease by 4%. Under the UKMO scenario, they predicted 15% increase in sorghum yields by 2030 with 6% increase in precipitation. Under the CCC scenario, sorghum yields increased by 70% in 2090 and was associated by 17% increase in precipitation. Under the wetter scenario (UKMO), predicted a 23% increase in precipitation, sorghum yields increased by 70% in 2090.

Rinaldi and Luca (2012) assessed climate change impacts on sorghum hay in Southern Italy using the Environmental Policy Integrated Climate (EPIC) model. Two future climatic scenarios (A2 and B1) obtained from three statistically downscaled GCMs namely; CCSM3, ECHAM and HadCM3 were employed in the study. Each GCM and every scenario were run for three time segments (2011-2040, 2041-2070 and 2071-2100). The simulated results indicated a decrease in the crop cycle duration and biomass in both scenarios and for all the three GCMs. The declining trends were more manifested in the A2 than B1 scenario and in last time slice (2071-2100). Dry plant biomass decreased by 5 t ha^{-1} and crop cycle duration shortened up to 20 days with the A2 scenario. CCSM3 and HadCM3 models produced more similar results. However, there was no large difference between A2 and B1 climatic scenarios for ECHAM model.

Potgieter *et al*. (2004) applied the use of shire-scale simulation models to investigate climate change impacts on wheat and sorghum production in the Banana and Emerald shires of central Queensland. They used four climate change scenarios (increase of temperature by 0.3°C and 1.9°C and rainfall changes of -13% and +7 %) derived from the CSIRO Mk3 Model for the year 2030 and 2070. There was a higher likelihood of yield decrease under the extreme scenarios of both temperature and rainfall (1.9°C and -13%); declining yields was larger for wheat than for sorghum, and also greater in the shire of Banana.

Srivastava *et al*. (2010) simulated sorghum by performing sensitivity analysis on the increase in temperature in India. One climate change scenario (A2a) from HadCM3 model outputs was used for three time slices 2020's, 2050's and 2080's. The outputs from the three time slices were then compared to the baseline conditions (1961-1990). The study highlighted a decrease in sorghum yield from 4% to 8% with 1°C increase in temperature during the rainy season in the regions where sorghum is grown. It was also noted that 2°C increase in temperature resulted to decreased yields of 8% to 15% for the winter sorghum. Simulation results using the A2a for the three future periods indicated sorghum yield decreases of 3% to 76% and 7% to 32% during the rainy and winter seasons, respectively.

Rao *et al*. (1995) investigated climate change impact on sorghum production in India using CERES-sorgum model. Three different regions were considered in the study (Hyderabad, Akola and Solapur). Three GCMs namely; GFDL, GISS and UKMO generated the scenarios for climate change. Under all the scenarios there was a reduction in both biomass and yield of sorghum at Akola and Hyderabad during the rainy season. An insignificant increase in yield was noted on sorghum grown at Solapur after the rainy season. The study also revealed that choice of the growing season as one of the major factors influencing the impacts of climate change on sorghum.

Chipanshi *et al*. (2003) assessed the vulnerability of sorghum and maize to climate change in Botswana using CERES-sorghum and CERES-maize model. Three GCMs namely, CCC, UKTR and OSU provided future scenarios of climate change. The results indicated that under the CCC and UKTR scenarios, sorghum yields are expected to decrease by 4.6% and 11.9% and 11.6 % and 22.5% in the eastern and western region of Botswana, respectively. On the other hand, under the OSU (wet scenario) sorghum yields increased by 13.8% and 7.2% in the eastern and western region, respectively.

Butt *et al*. (2005) investigated climate change impacts on sorghum yields in Mali. EPIC model and scenarios generated from two GCMs namely, UKMO and CCC models were used. The results depicted that sorghum yields are expected to decrease by 11.5% and 17.1% under both the UKMO and CCC scenarios, respectively.

Dimes *et al*. (2008) used APSIM model to investigate climate change impacts on crop production in Zimbabwe for 21st century. Outputs from 21 GCMs based on A1B scenarios of the Southern Africa were used in the stidy. The simulation results indicated a decrease of potential grain yield of sorghum by 6%, 16% and 22% as a result of effects of temperature, rainfall and combined effects of temperature and rainfall, respectively.

Nelson *et al*. (2009) compared yields of sorghum for 2000 and 2050 assuming two options: no climate change and climate change present. The effect of CO_2 in both cases was neglected. Two GCMs (CSIRO and NCAR) were used to simulate yield impacts for 2050. Both CSIRO and the NCAR scenarios projected an increase in both temperature and precipitation by 2050. In the no climate change condition, the results indicated that sorghum yields were projected to increase by 138.7% by 2050 within the developing countries. However, sorghum showed a decrease in yield under both scenarios for the developing countries with a decrease of 2.5% and 1.5% using CSIRO and NCAR models, respectively.

2.8 Conceptual Framework of the Study

The conceptual framework presents and explores the basic variables, their relationship and methods used to study the relationships. This study focused on modeling of impacts of climate change on sorghum production by application of APSIM crop model under two scenarios of climate change (RCP4.5 and RCP8.5) developed from CORDEX GCMs. Field experiments were carried out to measure parameters of sorghum cultivars, soil nutrients, levels of inorganic fertilizer used and different management practices employed. Observed daily climate data was used together with the field experimental data for APSIM model calibration and validation. Observed climate data was also used to validate the historical GCMs data before they could be used for impact study. The scenarios of climate change were used to create daily weather data for input into the crop model, so as to simulate sorghum parameters for both the baseline and the future and compare the two cases. The changes in sorghum growth and development were analyzed and viable adaptation options were identified (Figure 5) (see chapter on Data and Methods for more details).

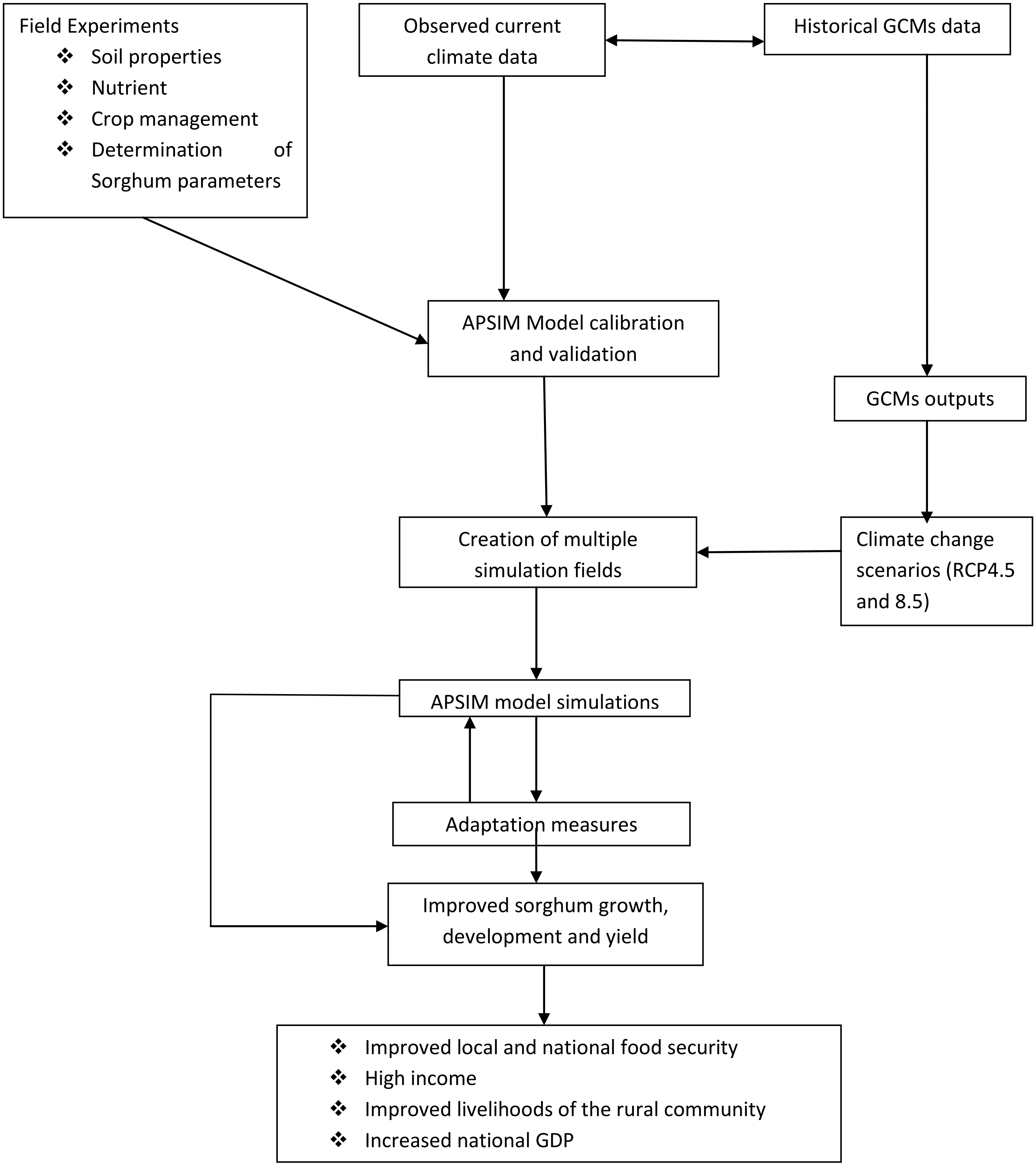

Figure 5: A conceptual framework showing key variables and their linkages, experiments and methods used to study the relationships

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter illustrates the types and sources of data, and the methodology employed in undertaking the research in order to achieve the overall and specific objectives in Section 1.5.

In the initial section, the datasets (climatic and non-climatic) used are described in details, while the last section is dedicated to detailed description of the various methods used to achieve each of the specific objectives.

3.2 Types and Sources of Data

3.2.1 Historical Climate Data

Daily observed climate data (rainfall, maximum and minimum temperature and solar radiation) for the period 1981 to 2012 for Katumani Agrometeorological station was employed in the current study. Monthly data from two other stations; Iveti (1981 to 2012) and Machakos DO (1981 to 2010) was also used in this study. These sets of data were obtained from Kenya Meteorological Department. Details of these sets of data are as outlined in Table 7.

Table 7: Details of the meteorological stations used in the study

Site	**Latitude**	**Longitude**	**Elevation**	**Data**					
				Rainfall		Temperature		Radiation	
				Daily	Monthly	Daily	Monthly	Daily	Monthly
Katumani	1.58°S	37.23°E	1592m	A	A	A	A	A	A
Iveti FRP	1.47°S	37.28°E	1890m	NA	A	NA	NA	NA	NA
Machakos D.O	1.52°S	37.27°E	1646m	NA	A	NA	NA	NA	NA

A= Available and AN= Not Available

3.2.2 COordinated Regional Downscaling EXperiment

Coordinated Regional Downscaling Experiment (CORDEX) GCMs were used to provide historical data (1951-2005) and to project changes in daily climate variables (rainfall, maximum and minimum temperature and solar radiation) for the study region for three future time slices: near-term, mid century and end century (2010-2039, 2040-2069 and 2070-2099). Out of 8GCMs available within the CORDEX only 7 GCMs (CanESM2, CNRM-CM5, NorESM1-M, EC-EARTH, MIROC5, GFDL-ESM2M and MPI-ESM-LR) were used. The HadGEM2-ES model was disregarded in the analysis because it assumes all months within a year to have 30 days. Two scenarios; RCP8.5 and RCP4.5 were employed in the current study to represent high emission and medium stabilization scenarios, respectively. More details on the GCMs and the RCPs considered in this study are as discussed in chapter two.

3.2.3 Historical Sorghum Yield Data

Annual sorghum yield data for Machakos County was obtained from the Ministry of Agriculture, Machakos County, Kenya for the period 1981 to 2012.

3.2.4 Soil and Crop Management Data

Soil data was obtained from the experiments which were carried out at KALRO Katumani. These included both physical and chemical properties of the soil. In addition the crop management data that was used to calibrate the APSIM model was obtained from the experimental fields in Katumani in 2014 and 2015. These include crop name, cultivar, planting date, plant spacing, row spacing, planting depth, days to 50% flowering, days to physiological maturity, biomass and grain yield.

3.2.5 Estimation of Missing Data and Quality Control

Prior to analysis and presenting of results, it is essential to discuss a number of significant uncertainties that are associated with the analysis of any data, which may be attributed to human and instrument errors. Analyses of climate parameters often require complete datasets with no missing records in between the time series. Thus, it is essential to fill in the missing data and check for homogeneity before any statistical technique is applied to it. There are several methods used to approximate the missing data. These include the correlation and regression methods, the mean method, amongst others. This study estimated the missing data using the correlation method (Equation 1).

$$X = r_{xy}.Y \text{ ……………………………………………………………………………… } (1)$$

In Equation 1: X is the missing climate data, Y is the climate data from the National Aeronautics and Space Administration (NASA) Prediction of World Energy Resources (POWER) Agroclimate Database and r_{xy} the correlation coefficient between the observed climate data and web based source data available at the following website:
(http://power.larc.nasa.gov/cgibin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov)

The database provides estimated daily satellite climate variables (e.g., rainfall, minimum and maximum temperature, and solar radiation).

Several methods for testing homogeneity of observed data have been proposed by several authors. These methods are categorized into two broad groups; the absolute and relative methods. In the absolute method, the test is applied for an individual station. On the other hand, the relative method incorporates the neighbouring (reference) stations in the testing (Wijngaard *et al.*, 2003). In this study, the absolute method (single mass curve analysis) was used for testing homogeneity. The method involves plotting cumulated climate data against time. For homogeneous records, the single mass curve appears as a single straight line, while heterogeneity is indicated by the existence of a shift in the cumulative line due to a shift in the mean. In literature, there exist several other methods for testing the homogeneity of climate variables (Kohler, 1949; Buishand, 1982; Alexanderson, 1986; Vincent, 1990; Peterson *et al.*, 1998; Ducré-Rubitaille *et al.*, 2003; Klingbjer and Moberg, 2003; Tomozeiu *et al.*, 2005; Staudt *et al.*, 2007; Modarres, 2008).

3.3 METHODOLOGY

3.3.1 Determination of the Variability and Trends of Climate Parameters and Sorghum Yield

Initially, the intra-seasonal rainfall characteristics; onset, cessation, duration and the rainy days were computed for each year. The variability and trends of the intra-seasonal rainfall characteristics; monthly, seasonal and annual rainfall, maximum and minimum temperature and annual sorghum yield were then determined using coefficient of variability (CV), linear regression and Mann-Kendall test. Variability and trends of solar radiation were not considered because solar radiation has a closer direct correlation with maximum temperature (Peng *et al*., 2004). Hence to avoid possible correlations among variables solar radiation was neglected in the analysis of variability and trends.

3.3.1.1 Determination of Intra-Seasonal Rainfall Characteristics

Katumani meteorological station was used to compute the intra-seasonal rainfall characteristics because it was the only station with daily rainfall.

In a season, onset and cessation of rainfall, which signifies the start and end of the seasonal rainfall, have been defined in different ways in several studies (Stern *et al.*, 1982; Sivakumar, 1988; Kasei and Afuakwa 1991; Omotosho *et al*., 2000; Dodd and Jolliffe, 2001; Stern *et al*., 2003; Tesfaye and Walker, 2004; Kihupi *et al*., 2007; Tadross *et al*., 2009; Marteau *et al*., 2011). In this study onset and cessation criterions by Stern *et al. (*1982) were adopted because it has been frequently used in African countries in many agro-climatological applications. Hence onset date was defined as the day after 1st March for MAM or 1st October for OND that received at least 20mm of rainfall which had accumulated over 3 successive days and with no dry spell exceeding 7 days within the next 30 days. The criterion for defining the onsets was informed by the broad perception that the MAM and OND seasonal rainfalls begin in March and October, respectively. The state of having no dry spell exceeding 7 days after the beginning of the growing season reduces the likelihood of a false onset. An episode of 30 days is the mean length for the first growth stage (vegetative phase) of most crops (Allen *et al*., 1998). After 30 days majority of the crops would have surfaced and be well established. Similarly, cessation date was defined as any day after 1st May and 1st December for the MAM and OND season, respectively, when the water balance becomes zero. This simply means that the water balance for the previous day plus the rainfall amounts less the evaporation for the present day results to a value equal to zero or negative. If the value is negative it’s replaced with zero since it’s not possible to have negative water.

The duration of the seasonal rainfall was determined by subtracting the onset dates from the cessation dates (Stern *et al.*, 1982; Tesfaye and Walker, 2004). Moreover, although rainfall measurements can be as low as 0.1 mm, a threshold value of 1mm was used to define a rainy day because a value of 0.1mm of rainfall more or less has no effect on growth of crops (Robel *et al.*, 2013) and is highly variable to instrumental errors. The rainy days were determined by counting all the days within the specific season with rainfall amounts greater than or equal to 1mm (Stern *et al.*, 1982; Segele and Lamb, 2005; Hadgu *et al.*, 2013).

Cumulative Ogive

The percentage cumulative mean rainfall was also used to establish the onset and cessation of the seasonal rainfall. In addition, it was also used to estimate the rainfall amounts and rainy days that had accumulated by time of start and withdrawal of the rains during both seasons. The initial step in this method was to obtain the mean rainfall amount and number of rainy days that occurred at each five day interval of each year for a specific season. The next step was to compute the percentage of the mean rainfall and rainy days that occurred at each pentad throughout each year for a particular season. Thirdly, the percentages of the pentads were cumulated. Finally, the cumulated percentage were plotted against the pentads, rainfall onset corresponded to the initial point of maximum positive curving of the graph, while the end of the rains corresponded to final point of maximum negative curving (Adejuwon *et al.*, 1990; Odekunle, 2006)

3.3.1.2 Variability of Climate Parameters and Sorghum Yield

To quantify the variability of the intra-seasonal rainfall characteristics; monthly, seasonal and annual rainfall, maximum and minimum temperature and annual sorghum yield, the coefficient of variation (CV) was computed as shown by equation 2. It is always expressed in percentage for ease of interpretation. Percentage Coefficient of variation values are classified as follows: < 20% less variable, 20-30% moderately variable, and > 30% highly variable (Hare, 1983; Araya and Stroosnijder, 2011).

$$Coefficient\ of\ Variation\ (CV) = \frac{Standard\ Deviation}{Mean} * 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 2)}$$

3.3.1.3 Trend Analysis

In a time series, a trend refers to a steady and regular movement through which the values are either increasing or decreasing (Gilbert, 1987). Parametric and non-parametric methods can be used to detect trends within a time series of any meteorological data. An assumption with the parametric methods is that data is assumed to be free from outliers and normally distributed. However, the non-parametric methods ignore such hypotheses and is less sensitive to outliers (Partal and Kahya, 2006; Yenigun *et al.,* 2008; Hadgu *et al.*, 2013; Gitau *et al.,* 2018). In this study the non-parametric (Mann-Kendall test) method was applied to study the existence of any significant trends in the onset, cessation, duration, number of rainy days, seasonal rainfall totals, annual rainfall totals, seasonal and annual maximum and minimum temperatures, and annual sorghum yield. The linear regression method was used to visualize and derive the magnitudes of trends.

Mann-Kendall Test

The Mann–Kendall test is largely used non-parametric test to detect significant trends in data over time (Modarres and da Silva, 2007; Wang *et al*., 2008; Zhang *et al*., 2011). This test does not necessitate the data to be normally distributed and is also less responsive to abrupt breaks due to inhomogeneity of the time series (Jaagus, 2006).

The Mann-Kendall test statistic (*S),* was computed using Equation 3,

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \qquad (3)$$

In Equation 3: *S* is the Mann-Kendall test statistic; x_i and x_j are the chronological data values of the parameter being considered in the years *i* and *j* (*j* > *i*) and *n* is the length of data series.

A positive and a negative value of S indicate an increasing and a decreasing trend in the data series, respectively. The specification of the sign function is as shown in Equation 4:

$$\text{sgn}\left(x_j - x_i\right) = \begin{cases} +1\ if\ \left(x_j - x_i\right) > 0 \\ \ 0\ if\ \left(x_j - x_i\right) = 0 \\ -1\ if\ \left(x_j - x_i\right) < 0 \end{cases} \qquad (4)$$

If the size of the sample being studied is greater than or equal to 10 ($n \geq 10$), the standard normal variable (*Z)* is computed using Equation 5 (Douglas *et al*., 2000; Yenigun *et al.,* 2008).

$$Z=\begin{cases}\frac{S-1}{\sqrt{Var\ (S)}}\ if\ S>0\\ 0\ if\ S=0\\ \frac{S+1}{\sqrt{Var\ (S)}}\ if\ S<0\end{cases}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

Positive and negative values of Z indicate increasing and decreasing trends, respectively. Determining the presence of statistically significant trends at an α significance level, two hypothesis (null and alternative) have to be tested by evaluating and comparing Z values with the ones obtained from the standard normal table.

The null hypothesis (H_o) indicates no significant trends while the alternative hypothesis (Ha) indicates presence of significant trends. Ho is rejected if $|Z| > Z_{\left(1-\frac{\alpha}{2}\right)}$ at any given level of significance. A significance level of α= 0.05 was used in this study.

Linear Regression

In regression analysis, the most important statistical parameter derived is the slope (a) which specifies the rate of change of the parameter over the years. Positive (negative) values of the slope represent an increasing (decreasing) trend. The linear regression equation is as shown in Equation 6. The linear regression makes a stronger assumption about the distribution of the dependent variable (Y) over time than does the Mann-Kendall. This test necessitates the data to be linearly distributed or else the data has to be transformed before testing for trend. This becomes tedious especially when many trends need to be examined.

$$Y = ax + b\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

In Equation 6: Y is the dependent variable, *x* is the explanatory variable, *a* is the slope and *b* is the intercept.

3.3.1.4 Response of Sorghum Yield to Climate Variables

The nature and degree of relationships between sorghum yield and climate at each growth stages and the total growing season were analyzed using correlation and multiple regression analyses. Sorghum has three broad growth stages, where growth Stage 1 (GS1) represents the vegetative phase, growth Stage 2 (GS2) the reproductive phase and growth Stage 3 (GS3) the maturity or grain filling phase. Daily rainfall and temperature for both the MAM and OND seasons were cumulated to account for each of the growth stages.

A simple correlation coefficient between sorghum yield and climate variables is given by Equation 7.

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \text{ ……………………………………………. (Equation 7)}$$

In Equation 7: *r* is the correlation coefficient, *x* is the climate variable, *y* is the sorghum yields and *n* is the number of observations.

So as to select the climate variables that are significant to the yield of sorghum, a step-wise multiple regression analysis was implemented. Within the step-wise method the forward selection method was selected which allows starting with a null model and thereafter adding variables sequentially. The yield and climatic parameters were expressed as dependent (Y) and independent variables (X), respectively. The general outline of the multiple regression equation is as presented in Equation 8.

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3 + \cdots b_nx_n \text{ ………………………..………………………… (8)}$$

In Equation 8: Y is the sorghum yield (dependent variable), a is the constant, b_i are the coefficients of x_i and x_i are the climate variables (independent variables).

3.3.2 Determination of the Effect of Cultivars, Nitrogen and Phosphorus Application Rates on Growth, Development and Yield of Sorghum

3.3.2.1 Soil Sampling

Preliminary soil sampling was done in the experimental field a day before sowing. A soil auger was used to get samples of soil at different soil depths (0-15, 15-30, 30-60 and 60-90cm) and placed into sampling bags. The conventional sampling technique (W-shaped) was utilized in this study because it is less costly as compared to the grid technique. The W-shaped sampling technique was used to obtain a minimum of 10 cores to ensure accurate representation of nutrients needs in the soil. These soil samples from each core were then mixed thoroughly to obtain a composite sample for the various soil depths. The soil samples were directly sent to the

National Agricultural Research Laboratory (NARL) in Kabete for the physical and chemical analysis.

Only the physical and chemical properties required as input parameters in the ASPIM model were analyzed. The physical properties analyzed include initial soil water content, bulk density, soil particle distribution (% of clay,% sand and % of silt), drained upper limit (DUL) or field capacity, saturated volumetric water content (SAT) and wilting point (LL15), similarly the chemical properties analyzed included the available phosphorus, effective cation exchange capacity (CEC), exchangeable bases (Calcium, Magnesium, Sodium and Potassium), soil organic carbon, soil pH, soil total nitrogen, finert (fraction of soil organic matter which is not vulnerable to decomposition) ,fbiom (fraction of soil organic matter that is decomposable and originally present in the fast decomposing pool) and initial ammonium and nitrate concentrations.

3.3.2.2 Field Experiment Design and Treatments for Model Calibration and Evaluation

The test crop in the field experiments was sorghum. Two cultivars of sorghum, the early maturity Gadam and the late maturity Seredo were planted in the experimental plots at the research station in Katumani (01°35’S; 37°14’E) during the MAM and OND growing seasons for the years 2014 and 2015. The experiments were used to assess the use of APSIM-Sorghum model in modeling future climate change impacts on growth, development and yield of sorghum in Machakos County.

To calibrate the APSIM-Sorghum model within the study area, field experimental plots of 6 m by 7.5 m (45 m^2) in size were established for four seasons (March to May and October to December, 2014 and 2015). The experiments were laid out in a Randomized Complete Block Design (RCBD) with two replications. Inter-row (between rows) and intra-row (within rows) spacing were 0.75m and 0.20m, respectively, because for drier and less fertile conditions, wider spacing and low plant population are highly recommended for optimum sorghum growth (AIC, Kenya 2002).

Sorghum was sown in furrows because the seeds were too small to be spaced apart like corn. More seeds were planted than needed then thinned two weeks after emergence to allow a spacing of 20cm within the rows. The blocks and plots were alienated from each other by a distance of

2m and 0.5m, respectively to prevent cross contamination of treatments between blocks and plots. Guard rows of Gadam cultivar were planted to limit bird damage and also to reduce the impact of other factors outside the experiments (Figure 6).

There were four levels of nitrogen [0, 50, 75 and 100 kg Nha^{-1}] and three levels of phosphorous [0, 50 and 100 kg P_2O_5 ha^{-1}] (Table 8). The twelve (12) different treatments are presented in Table 8. P_2O_5 was applied as diammonium phosphate $(NH_4)_2HPO_4$ at sowing, while nitrogen was applied as ammonia nitrate (NH_4NO_3) 35 days after sowing. The choice of the different levels was based on the fertilizer recommendation rates by KALRO, which is 88 kg N ha^{-1} and 92 kg P_2O_5 ha^{-1} (UNDP/FAO, 1975; FURP, 1994).

Table 8: Treatments with different levels of inorganic fertilizer

Treatment combination	N (kg/ha)	P_2O_5(kg/ha)	Treatment
N1P1 (Control)	0	0	T1
N2P1	50	0	T2
N3P1	75	0	T3
N4P1	100	0	T4
N1P2	0	50	T5
N2P2	50	50	T6
N3P2	75	50	T7
N4P2	100	50	T8
N1P3	0	100	T9
N2P3	50	100	T10
N3P3	75	100	T11
N4P3	100	100	T12

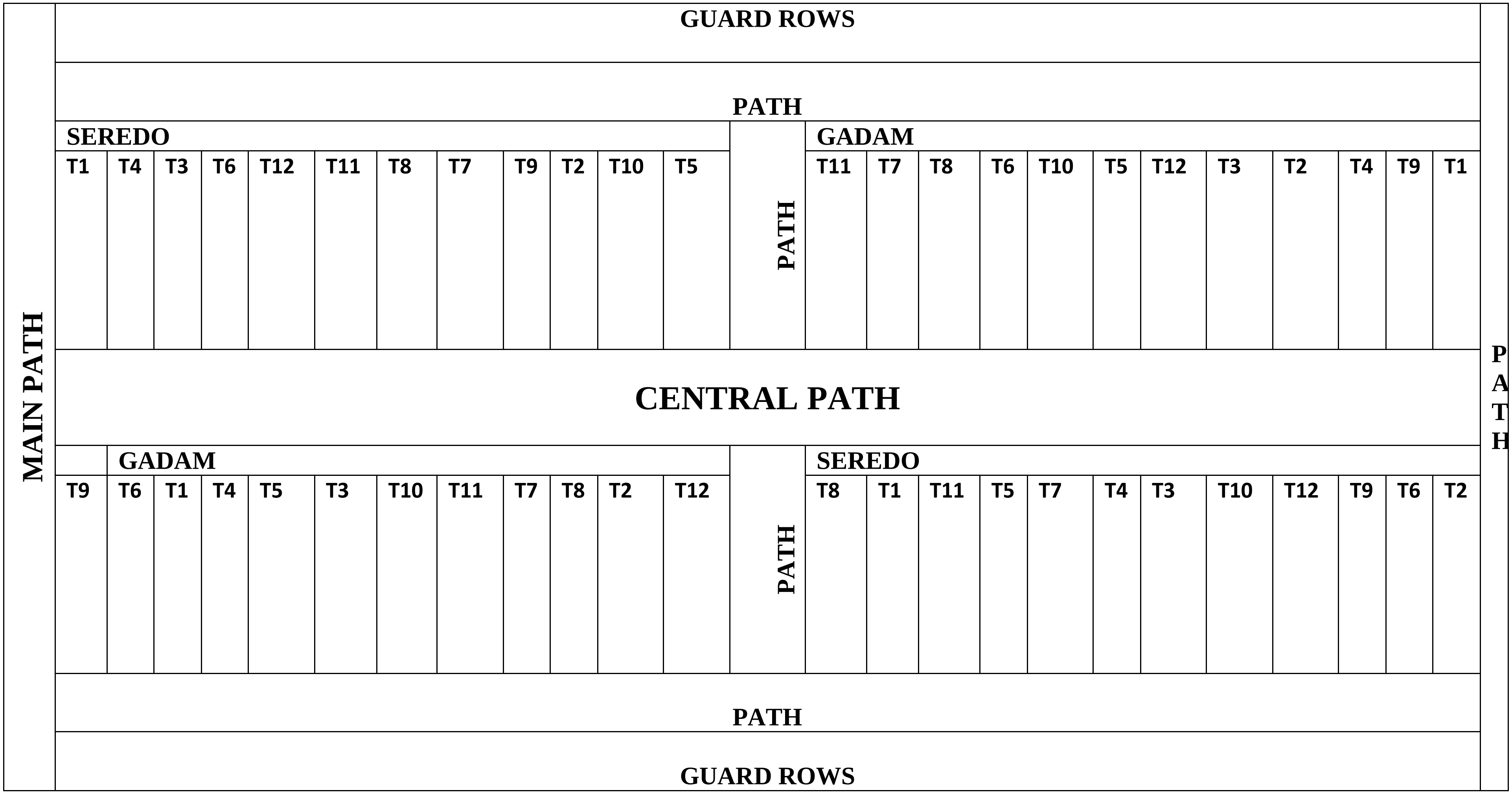

Figure 6: Experimental Field Layout

Design: Randomized Complete Block Design **Net Plot size**: 6 x 7.5m **Replication**: Two

Treatments: Cultivars (Main Plot); Gadam and Seredo
Nitrogen and Phosphorus levels (Sub-plots)

3.3.2.3 Field Measurement of Sorghum Parameters

Data was collected from the vegetative phase to the maturity phase with the following parameters being recorded:

3.3.2.3.1 Date of Emergence of Plants

Few rows in randomly selected plots were marked and observed to determine the date of emergence. The emerging seedlings were tallied at intervals of 2 days until emergence stoped. Emergence ceased when at least 50% of the plants had the collar of the 5th leaf was visible.

3.3.2.3.2 Days to 50% Flowering

Excluding the border rows, two rows from all sides of every plot were selected and marked. Sorghum plants in the marked rows were monitored and the dates of 50% flowering were recorded. The date of 50% flowering was identified when at least half of the sorghum plants in the plot showed exposed anthers at the middle of the panicle. Days to 50% flowering were then calculated from the sowing date by deducting the date of sowing from date of 50% flowering.

3.3.2.3.3 Days to Physiological Maturity

Plants from the marked rows were monitored and the dates of physiological maturity were documented. Maturity was determined by identifying the date of the appearance of a black layer at the point of attachment of the grain to the panicle. This method is an accurate predictor of physiological maturity since it corresponds with the cutoff of assimilates being translocated into the kernel. The date of the black layer is easy to measure since it can be observed in the field without the use of special tools (Eastin *et al.*, 1973). Days to physiological maturity were then obtained by deducting the date of sowing from date of physiological maturity.

3.3.2.3.4 Grain Yield

At harvest, in order to determine the grain yield of sorghum, an area of 3m by 3m (representing the central area) was harvested in all the experimental plots. The central plot was chosen for harvesting because it’s assumed to be less affected by cross contamination of treatments. Harvesting was done after the crop had attained physiological maturity. The number of plants harvested in each of the plots were counted and recorded.

All panicles were cut at the base of the head, counted and the fresh weight determined. A few representative panicles were selected and the grains threshed. The fresh weight of the grain was determined and recorded. The grain sub-samples for each cultivar and replicate were then placed in an oven to dry at 70°C for 2 days (48 hours) until a constant weight was attained. The dry weights measurements were taken and their weight recorded. Dried weight of the grains was used to establish the harvested area dry weight which was finally expressed as kg/ha.

3.3.2.3.5 Total Above Ground Biomass

At maturity biomass was harvested by cutting a few sorghum plants immediately above the ground surface and their fresh weight recorded. Sub-samples (leaves, stems, husks and grain) of the sorghum plants for each cultivar with known fresh weight were then dried in an oven at 70°C until a constant weight was attained. The dry weights measurements were taken and their gross weight recorded Above-ground biomass was obtained by subtracting the dry weights from the fresh weights. This was then expressed as kg/ha in a similar way as the grain yield.

3.3.2.4 Statistical Analysis

The effect of crop cultivar, nitrogen and phosphorus levels on the field measurements of sorghum parameters were analyzed using the analysis of variance (ANOVA) structure in DSAASTAT version 1.514. DSAASTAT is an excel macro used to perform basic statistics analyses on agricultural experiments. ANOVA was executed on the field data which was obtained in the above subsection (3.3.2.3). ANOVA was used to test the null hypothesis (all treatment means are equal) and alternative hypothesis (at least one treatment mean is different). F- Test was used to determine the hypothesis to be accepted. Significantly different treatment means were identified using Fishers Least Significant Difference (LSD) at $P< 0.05$.

$$LSD = t_{\alpha/2}\sqrt{MSE\left(\frac{2}{n}\right)} \quad \text{……………………………………………………………..…….} \quad (9)$$

$$\boldsymbol{if} \ \left|\overline{y_i} - \overline{y_j}\right| \geq \boldsymbol{LSD}, reject\ null\ hypothesis$$

In Equation 9: t is the critical value from the t-distribution table, MSE is the mean square error obtained from the ANOVA test, n is the number of observations, ybar is the treatment mean, ‘i’ and ‘j’ represents two different treatments

3.3.3 Assessing the Capability of APSIM-Sorghum Model to Simulate Growth, Development and Yield of Sorghum Planted in Different Seasons

3.3.3.1 Data Requirements for APSIM

Before any simulation in APSIM is preceded, the model is first configured by identifying the modules to be applied in the simulation and the sets of data needed by those modules. As the simulation continues, the modules in APSIM normally need initialization data and temporal data. In general the initialization data is categorized as either generic data (defines the module for all simulations) or precise simulation parameter data for example cultivar, management and site characteristics.

Typical site parameters are soil parameters (bulk density, soil particle size distribution, drained upper limit (DUL), saturated volumetric water content (SAT), wilting point (LL15), available phosphorus, soil organic carbon, soil pH, soil total nitrogen, effective cation exchange capacity (CEC), exchangeable bases, etc.) for soil modules, daily climate measurements (rainfall, solar radiation, maximum and minimum temperatures) for meteorological modules and management data such as timing of agronomic practices and fertilizer types and amounts and for the management module.

3.3.3.2 APSIM Model Calibration

Calibration of any model is the adjustment of parameters and functions of that model so that the simulations are the same or very close to data obtained from the experimental field. APSIM does not offer any programmed procedures for calibration. So as to calibrate the APSIM model for specific conditions the parameters of the model were changed manually one at a time and quantitative comparisons of model output to observations made. The APSIM model was calibrated using crop growth and development parameters for sorghum. These parameters are the genetic coefficient of the two sorghum cultivars (Gadam and Seredo).

When using a cultivar that is not already calibrated, it is recommended that an existing cultivar that is close to be used. The crop module in APSIM has descriptions of Pioneer_S34 and Texas_RS610 which have parameters very similar to Gadam and Seredo, respectively. Hence parameters of Pioneer_S34 and Texas_RS610 incorporated in APSIM were chosen to describe the Gadam and Seredo varieties, respectively. Soil characteristics used were those typical of soils in Katumani, in Machakos. The maximum available water content of the soil at sowing was adjusted to 20 % filled from the top. This meant that the top layer of the soil was totally filled with water, then the second layer filled from the top, then the third etc, until all the 20% of the maximum available water was used. This suggested that the top layers of the soil profile were absolutely wet while the bottom layers were dry. The entire soil profile had 20% of the maximum available water. The initial mineral N of the soil profile was set at 48.5 $kgha^{-1}$ Nitrate (NO_3) and 14.43 $kgha^{-1}$ Ammonium (NH_4). The sowing rule was set so that sowing took place when there was an accumulation of 20 mm of rainfall within three successive days as per the onset dates criteria. The sowing dates were set to 2nd April 2014 and 20th October 2014 for the MAM and OND seasons, respectively. The seeds were planted at a depth of 30 mm. The row spacing was kept at 0.75m with the plant to plant distance of 0.2m to give a plant population of 7 plants per m^2. Nitrogen was applied at 0, 50, 75 and 100 kg Nha^{-1} at 35 days after sowing (DAS) in the form of Ammonium Nitrate (NH_4NO_3). Traditional land preparation, such as ploughing, was employed**.**

Surface organic matter, soil water and soil N were reset to initial conditions four weeks before the date of sowing of each season so as to remove carry over effects and to let the soil conditions equilibrate with the current weather conditions. This was done to remove most of the bias from the specified initial condition. The parameter *U*, which illustrates the initial phase (when there is adequate water in the soil that is when evaporation rate is constant) of evaporation of water from the soil was set at 6mm day^{-1}, while *Cona*, which characterizes the second phase of soil water evaporation (falling rate of evaporation) was set at 3.5 mm day^{-1} in the APSIM soil module, these are values accepted in the tropics (Chikowo, 2011; Keating *et al*., 2003; Probert *et al*., 1998). SWCON which is a coefficient that indicates the fraction of the water in excess of field capacity that drains to the adjacent layer in a single day was set to 0.7 since the soil is sandy (Chikowo, 2011; Probert *et al*., 1998). Phosphorus (P) was assumed to be non-limiting.

A composite met file containing daily climate data in column from 1st January 1985 to 31st December 2015 was created by converting the PRN file to met file in DOS window. TAMET software was then applied to confirm consistency of the data (Wall, 1977).

Tav_Amp.exe file was also applied in the study. It is a Microsoft DOS program written in FORTRAN language (Hargreaves, 1999). It reads a selected met file, calculates the values for annual average ambient temperature (TAV) and annual amplitude in mean monthly temperature (AMP) and generates a new met file with the computed values of TAV and AMP added after the keywords TAV and AMP. A new comment is inserted before the inserted values of TAV and AMP which denotes the time and date of insertion and the beginning and end of the period over which the data is calculated.

The Tav_Amp file was then run and applied to the generated composite met file so as to generate and add values of TAV and AMP. These values are then used by the soilN module in APSIM to estimate the daily soil temperature for the site (Hargreaves, 1999). Daily weather data (solar radiation, rainfall amount, minimum and maximum temperature) for the study region were then retrieved from the “met” module.

Data from the field observation experiment for MAM and OND 2014 growing seasons at Katumani on phenological dates (days to 50% flowering and physiological maturity), biomass and grain yield for the best treatment were used for the model calibration. Accumulated thermal times were obtained using the algorithm explained by Jones and Kiniry (1986) using weather data and observed phenology. Both data sets were used to approximate the genetic coefficient associated with the thermal time accumulations for the important growth stages. The genetic coefficients of sorghum were obtained by repeated simulations until a close relationship between the observed and simulated phenology, growth and yield parameters were obtained.

After model configuration with the required input data the APSIM model was run and simulated phenological dates, total above ground biomass and yield of sorghum were compared to observed measured values.

3.3.3.3 APSIM Model Evaluation

The accuracy of the calibrated model was evaluated by comparing observed values for phenological dates, biomass and yield for the two sorghum cultivars with those from model simulations at different rates of N application rates. Performance of the crop model was assessed using the modified index of agreement (d_m), Coefficient of Determination (r^2) and root mean square error (RMSE). More details are discussed in the next sub-sections.

3.3.3.3.1 Modified Index of Agreement

The modified index of agreement is the reformulation of the original Willmott's index of agreement (d). The modification was due to the fact that the index of agreement (d) is sensitive to outliers in any set of data as a result of the squaring of the difference term (Willmott, 1981). The use of the index of agreement shows that even for a poor model fit, relatively high values of the index may be obtained (Willmott, 1984). In order to conquer these drawbacks, Willmott *et al.*, (2012) introduced the modified index of agreement, defined as shown in Equation 10

$$d_m = 1 - \frac{\sum_{i=1}^{n} |O_i - S_i|}{\sum_{i=1}^{n} (|S_i - \bar{O}| + |O_i - \bar{O}|)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

In Equation 10: S_i, O_i, $and\ \bar{O}$ are the ith simulated, ith observed and average observed values, respectively and n the number of simulated-observations pairs.

The modified index of agreement (d_m) varies from 0 (complete disagreement between the observed and simulated values) to 1 (complete agreement between the observed and simulated values) with higher values indicating a better fit of the model and that the simulated values are more reliable.

3.3.3.3.2 Coefficient of Determination

The coefficient of determination (r^2) is defined as the squared value of the coefficient of correlation. It may also be expressed as the squared ratio between the covariance and the multiplied standard deviations of both the observed and simulated values (Equation 11). Therefore it estimates the combined dispersion against the single dispersion of the observed and simulated values. The coefficient of determination ranges between 0 (no linear correlation) and 1 (there is correlation that is dispersion of simulation is equal to the observation). The major drawback in this method is that only the dispersion is quantified, hence, a model which systematically over or underestimates at all times will still result in a value of r^2 close to 1.0 even if all simulations were inaccurate (Krause *et al.*, 2005; Moriassi *et al.*, 2007).

$$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})}\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})}}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

In Equation 11: S_i, O_i, $\bar{O}$ and $\bar{S}$ are the i^{th} simulated, i^{th} observed, average observed, average simulated values, respectively, while n is the number of simulated-observations pairs.

3.3.3.3.3 Root Mean Square Error

The root mean square error (RMSE) is commonly used in determining the difference between simulated values and the actual observations (MacLean, 2005). It is computed as shown in Equation 12. The RMSE ranges between 0 to infinity with a perfect score at 0. Lower values indicate that simulated values closely match the observed values.

$$\text{RMSE}= \sqrt{\frac{1}{n}\sum_{i}^{n}\left(S_i - O_i\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

In Equation 12: S_i, and O_i, are the i^{th} simulated and i^{th} observed values, respectively and n is the number of simulated-observations pairs.

3.3.4 Assessing the Performance of CORDEX in Simulating Climate Parameters

This section presents various indices that were used to evaluate the performance of the seven CORDEX models and the ensemble in simulating rainfall, temperature and solar radiation over Machakos County, Kenya. The analysis aided in the ranking of the most suitable GCMs that were used to evaluate impacts related to sorghum production.

There is no one method that has been universally accepted to evaluate the performance of GCMs in simulating climate variables. However, the type and number of assessment criteria used dictates the performance of models (Schaller *et al., 2011*). In this study, two metrics were applied to show the agreement between the simulated (S) and the measured observations (*O).* The two metrics include: the modified index of agreement (d_m) and root mean square error (RMSE) **(see section 3.3.3.3)**. The motivation of using the two metrics was drawn from the fact that a GCM which performs relatively well for a certain metric does not automatically perform well for a different metric.

Prior to assessing the performance of the GCMs in simulating observed data, it is essential to explain the characteristics of the data (observed and model). Box plots were used to examine/demonstrate the GCM outputs and observed data.

3.3.4.1 Box Plots

Box plots were used to examine the location, spread and skewness of rainfall, temperature and solar radiation within the study area. The interquartile range (50%) is indicated by the size of the box and the line across the center of the box marks the median (central observation). The range of the data from the minimum and maximum value is indicated by the whiskers attached to the box and the outliers are specified using markers with black color.

3.3.4.2 Multi-Model Ensemble Averaging

Given that individual models are always assertive (Weigel *et al.*, 2008) and that ensemble accommodates information from each individual model (Pincus *et al.*, 2008), multi-model ensembles are generally known to perform better than individual models (IPCC 2001, Duan and Phillips 2010, Miao *et al.*, 2013). Hence averaging the models usually enhances the skill, accuracy, reliability and consistency of a climate model.

According to Miao *et al.* (2014), there are several types of ensemble methods including the Bayesian model averaging (BMA), reliability ensemble averaging (REA) and simple model averaging (SMA techniques. In this study, the SMA technique was employed because of its simplicity. In this technique each model is assigned equal weights ($w_n = 1/n$, where n is the number of climate models) in the ensemble prediction. The limitation in this method is that, any information regarding the performance of the climate model is ignored (Casanova and Ahrens 2009).

3.3.4.3 Model Ranking

Assessing the performance of GCMs using a range of statistical methods assists in examining the pros and cons of every GCM from a range of statistical indicators with regard to observational dataset. However, using a wide range of metrics brings some challenges especially when interpreting the results. In a number of studies, researchers have done away with those metrics, and presented their ranking with a few of their earlier selected metrics (Werner, 2011). While in other studies, each metric is assigned weights and then overall ranking is calculated on the basis of the weighted methods (Rupp *et al*., 2013).

According to Stainforth *et al*. (2007) response of any climate model must not be weighted but accepted or eliminated. From this point of view, in this study the models were ranked based on each metric and for each climate variable. Within each method, poor performing GCMs are eliminated (GCMs with lowest rank), and hence ranks acquired by each of the metrics are scrutinized to circumvent the probability of overrating of the model. In order for the methods to be objective, the metrics were treated in the same manner, given that addition of weights will be based on an added assumption, which might increase the uncertainty.

Rankings were based on the number of GCMs used and hence in this study since seven (7) GCMs and the ensemble were employed, ranks were assigned from one (1) to eight (8) for each metric. In simplicity, the performance of every GCM was compared to the observed data and accordingly assigned a rank of one (1) to eight (8) on each metric, where one (1) shows the most efficient and eight (8) represents the worst performance on a particular metric. Rank sum is the summation of ranks obtained for rainfall, maximum and minimum temperature and solar radiation in each method for a GCM. Overall rank sum is the summation of rank sum for all the two metrics and was used to select the best performing GCMs in simulating climate variables. The lowest overall rank sum gave the best model to be used for impacts studies related to crop production.

3.3.5 Assessing Climate Change Impact on Growth, Development and Yield of Sorghum using APSIM-Sorghum Model

3.3.5.1 Climate Change Scenarios

Crop models have been used widely in the study of climate change impacts on the growth and yield of crops. They may involve direct and indirect (use of weather generators to process data) application of outputs from climate model as input to run the crop simulation models (Challinor *et al.,* 2009). However, in a few cases, observed climate data may be perturbed using the outputs from climate model (Hewitson, 2003; Challinor *et al*., 2009), thus generating climate change scenarios. In this study, the three climate scenarios from CORDEX (2010-2039, 2040-2069 and 2070-2099) for RCP 4.5 and RCP 8.5 were generated by perturbing the observed climate data for Katumani meteorological station through use the deltas (mean changes) of selected solar radiation, temperature and rainfall. The delta method exacts a change factor from the projected future climates covering all the CORDEX GCMs onto the hindcast climate data and generates distributions that exhibit the expected variations from the baseline period (1976-2005) in the GCM.

The use of deltas in the current study was done via the "climate change" module in APSIM, a technique which has been applied in related studies (Crimp *et al.,* 2008; Dimes *et al.,* 2008; Makuvaro, 2014; Hayman *et al*., 2010). The climate control module permits one to perturb solar radiation, temperature and rainfall of the current climate by different specified magnitudes obtained when computing the deltas. The sorghum module in APSIM version 7.8 includes changes in atmospheric CO_2 concentrations. Hence, the level of CO_2 concentrations was also specified in the climate control component. However, sorghum is not parameterized for CO_2 concentration levels other than a default of 350 ppm. This could be attributed to the fact that previous studies on the impact of CO_2 fertilization in sorghum showed insignificant increase in the yield of sorghum with the increase of CO_2 as it is already saturated with CO_2 (Von Caemmerer and Furbank, 2003; Seneweera and Norton, 2011; Sultan *et al*., 2013).

3.3.5.2 Simulation of Management Data for Impact Study

Details of the simulations are as discussed in section 3.3.3.2 with some minor adjustments on the following: maximum available water content of the soil at the beginning of the simulation was adjusted to 10% filled from the top. This was identified suitable because of the time lag between resetting to initial conditions and sowing. The sowing window was kept between 1st April and 15th April for MAM season and 10th October and 25th October for the OND growing season. For scenario analyses a sowing window is always specified to ensure sowing of the crop occurs close to the onset of the rainy season and capture the likelihood of changes of future rainfall patterns. This enables the model to capture a suitable sowing condition.

Phenological dates, total biomass and grain yield of sorghum were simulated under both current and changed climate. For the baseline period, concentration of CO_2 was set at 350 ppm and rainfall, temperature and solar radiation changes were all set to zero. Three future climate change scenarios examined were based on the RCP4.5 and RCP8.5 (described in section 2.5.2).

3.3.5.3 Uncertainty and Confidence Assessment

Uncertainty in the climate change projected impacts on sorghum parameters was evaluated through comparison of mean, standard deviation, changes in the mean and coefficients of variation of sorghum parameters in the baseline period and the projected scenarios. These statistics were determined for each sorghum cultivar, climate model and RCP.

GCMs with similar sign of mean change across the RCPs were used to establish the level of confidence in the direction of sorghum parameters. Percentage coefficients of variation were compared for GCMs and RCPs, so as to identify the sources of uncertainties. It’s a measure of farmer’s risk, high and low CVs signify high and stable inter-annual variability, respectively (Rosenzweig and Tubiello 2007).

3.3.6 Evaluation of Different Agronomic Management Practices

In order to curb climate change impacts on agricultural productivity and maximize yields, suitable agronomic management options have to be put in place. Some of the possible management practices include modification of management operations for example application of fertilizer, plant population and sowing dates. The normal plant population used in the region is 66,666 plants ha^{-1}. Increasing the plant population may lessen the loss of water through soil evaporation and thus increasing water use efficiency during the growing season. However, if there is water shortage mainly during seed filling, yields will be reduced thus decreasing the planting density should benefit yield.

In this study the simulations were run using planting densities below (53,333 plants ha^{-1}) and above (88,888 plants ha^{-1}) those currently practiced (66,666 plants ha^{-1}). Nitrogen fertilizer application rates were maintained at 0 and 50kgha^{-1}.

3.4 Assumptions and Limitations

Some of the limitations of the research undertaken were that the impact on sorghum production due to other factors other than the weather were not considered, this is because APSIM model simulations presumes that there are no effects of diseases, pests, weeds and water logging. Since changes in crop management did not occur, it is assumed that there were no changes in physical and chemical soil characteristics in the future, thus it was further assumed that only the weather conditions were vital to variations in the sorghum parameters. It was also assumed that both the climate data and production figures are accurate.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the results obtained when the various methods outlined in section 3.3 were applied to achieve the overall and specific objectives of the study as numerated in section 1.5. The results of variability and trends are presented and discussed first.

4.2 Variability and Trends of Climate Parameters and Sorghum Yield

4.2.1 Determination and Variation of Intra-Seasonal Rainfall Characteristics

Based on the definition of onset, the results obtained are as shown in Figure 7. The long term onset for MAM and OND seasonal rainfall ranged between 1st March and 28th April and 8th October and 27th November, respectively. The long term mean onset for MAM and OND seasonal rainfall was 26th March and 1st November, respectively (Table 9). These dates could be taken as reliable planting dates within the study area. By the time of the onset, the station records 22% and 13% of the total seasonal rainfall and 19% and 14% of the total number of rainy days for both MAM and OND growing seasons, respectively (Figure 8).

Since rainfall in the study area was highly variable, this means that in a typical growing season sowing of sorghum seeds should be done prior to or on the onset. Planting after the onset may result in sorghum failure, which may necessitate replanting or reduced sorghum yield as a consequence of unmet water requirements by the sorghum crop. The cumulated percentages of total seasonal rainfall and rainy days at the time of onset are enough to allow for the germination and establishment of the seeds. The attribution being that at the beginning of the growing season, less water is required (1 to 2.5mm/day) (Stichler and Fipps, 2003) because the plants are young and transpiration is low due to plants having small leaf surface area index. The water requirements then increases in the reproductive phase (flowering and seed setting) to around 7 to 10mm/day (Stichler and Fipps, 2003) to allow for seeds to achieve their maximum weight.

The long term rainfall cessation for MAM and OND ranged between 1st May and 7th June and 1st December and 31st December, respectively. The long term mean cessation for MAM and OND seasonal rainfall was 14th May and 12th December, respectively (Table 9). By the time the rainfall was retreating the station had received 94% and 87% of the total seasonal rainfall and 90% and 86% of the total rainy days for both MAM and OND growing seasons, respectively (Figure 8). This indicated that the susceptibility of the reproductive phase to water stress was minimal. The remaining percentages of the cumulative total seasonal rainfall and rainy days for both MAM and OND growing seasons was most likely enough for the sorghum crop to attain maturity. Daily water use by the sorghum plant is known to decrease steadily during grain filling as the leaves begin to senescence and the plant approaches physiological maturity.

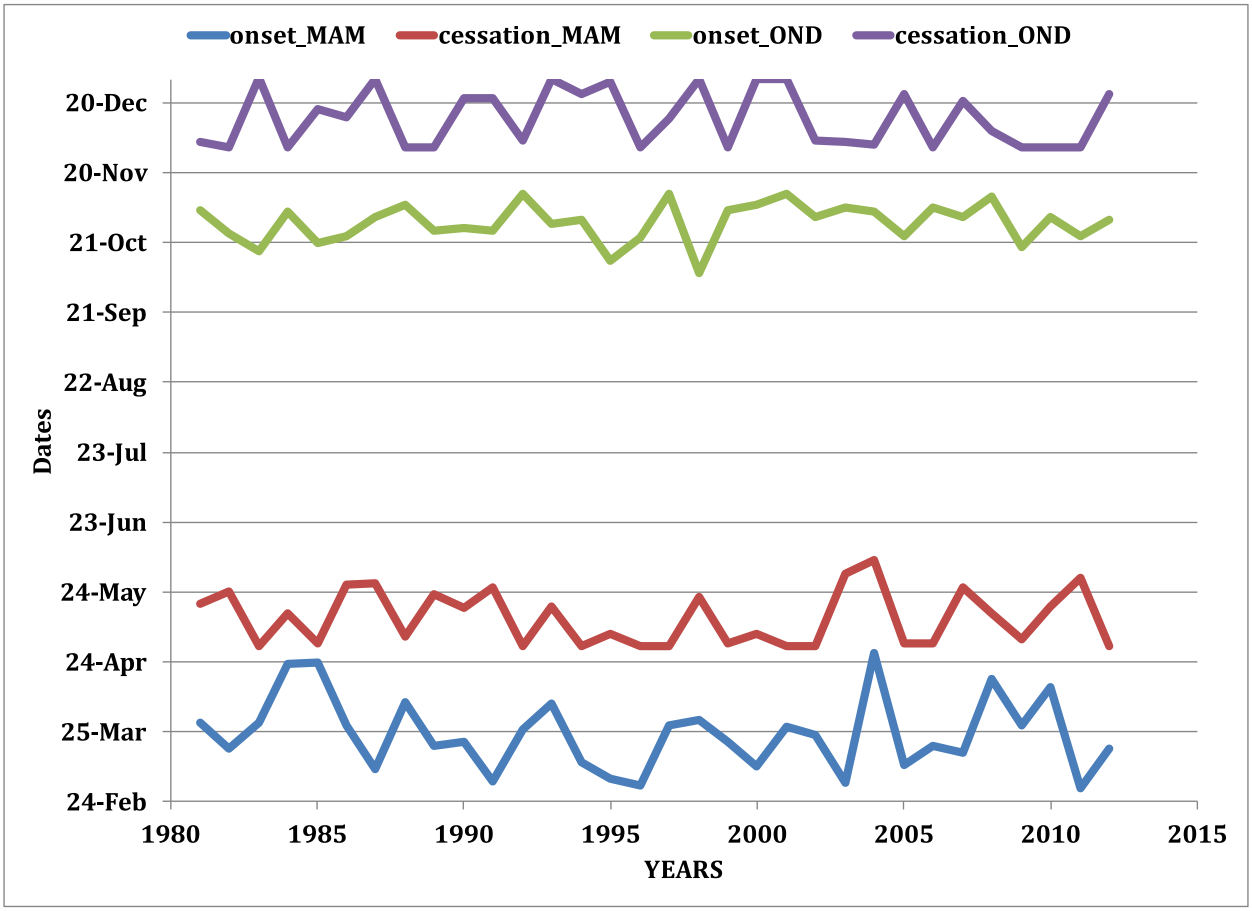

Figure 7: Rainfall onset and cessation dates for Katumani Meteorological station for the period 1981 to 2012

The onsets dates were highly variable compared to the cessation dates for both growing seasons (MAM and OND). However, the variability in the onsets was relatively higher during MAM growing season (Table 9). While cessation can occur as early as 1st May and 1st December during MAM and OND season, it can extend to 7th June and 31st December. A remarkable characteristic from this is that though cessation dates vary inter-annually like onset, the magnitude of variation of the cessation (15.9% and 15.3% for MAM and OND season) was not as elevated compared with onset (62.3% and 34.0% for MAM and OND season). Camberlin and Okoola (2003); Mugalavai *et al*. (2008); Recha *et al.* (2011) reported similar larger variability in onset compared to cessation dates for the wider Eastern Africa region. Hence, decisions associated with crop harvesting, transportation, storage and marketing are more easily made and that the recommendations related to land preparation and crop planting should be taken with great caution.

Generally the duration and number of rainy days were highly variable (32.5% to 42.2%) indicating high year to year variability of the length of the growing season and number of rainy days. However, the variability was slightly higher during the MAM growing season (42.2% and 36.6%) as compared to the OND season (41.1% and 32.5%). Higher variability on the seasonal rainfall duration within the study area could be attributed to higher variability in the onset dates. This is because the seasonal rainfall duration is highly correlated to the rainfall onset (Mugalavai *et al.*, 2008). Higher coefficient of variation on seasonal rainfall duration presents less confidence in the choice of crops and cultivars based on growth cycle. On the other hand, higher variability of rainy days shows less dependency of the rainy days for planning agricultural activities which may in turn lead to crop failures. This is true especially for farmers who lack the instruments to quantify the rainfall amounts but rather depend on rainy days to plan cropping calendar.

Since the intra-seasonal rainfall characteristics for the MAM season are characterized by high variations as compared to those of the OND season in Katumani, the MAM season is therefore said to be unreliable in terms of rain-dependant crop production resulting to less dependency on the rains for planning any agricultural activity.

Table 9: Descriptive statistics of intra-seasonal rainfall characteristics at Katumani Meteorological Station during MAM and OND seasons for the period 1981 to 2012

Seasonal Rainfall Characteristics	**Descriptive Statistics**	**MAM**	**OND**
Onset	Latest (day/date)	119 (28th April)	332 (27th November)
	Earliest (day/date)	61 (1st March)	282 (8th October)
	Mean (day/date)	86 (26th March)	306 (1st November)
	Standard Deviation (days)	16	11
	CV (%)	62.3	34.0
Cessation	Latest (day/date)	159 (7th June)	365 (31st December)
	Earliest (day/date)	122 (1st May)	336 (1st December)
	Mean (day/date)	135 (14th May)	347 (12th December)
	Standard Deviation (days)	12	11
	CV (%)	15.9	15.3
Duration	Longest (days)	90	83
	Shortest(days)	20	18
	Mean (days)	49	42
	Standard Deviation (days)	21	17
	CV (%)	42.2	41.1
Number of Rainy Days	Maximum (days)	40	55
	Minimum (days)	8	10
	Mean (days)	24	28
	Standard Deviation (days)	9	9
	CV (%)	36.6	32.5

MAM: March-April-May, OND: October-November-December, CV: Coefficient of Variation

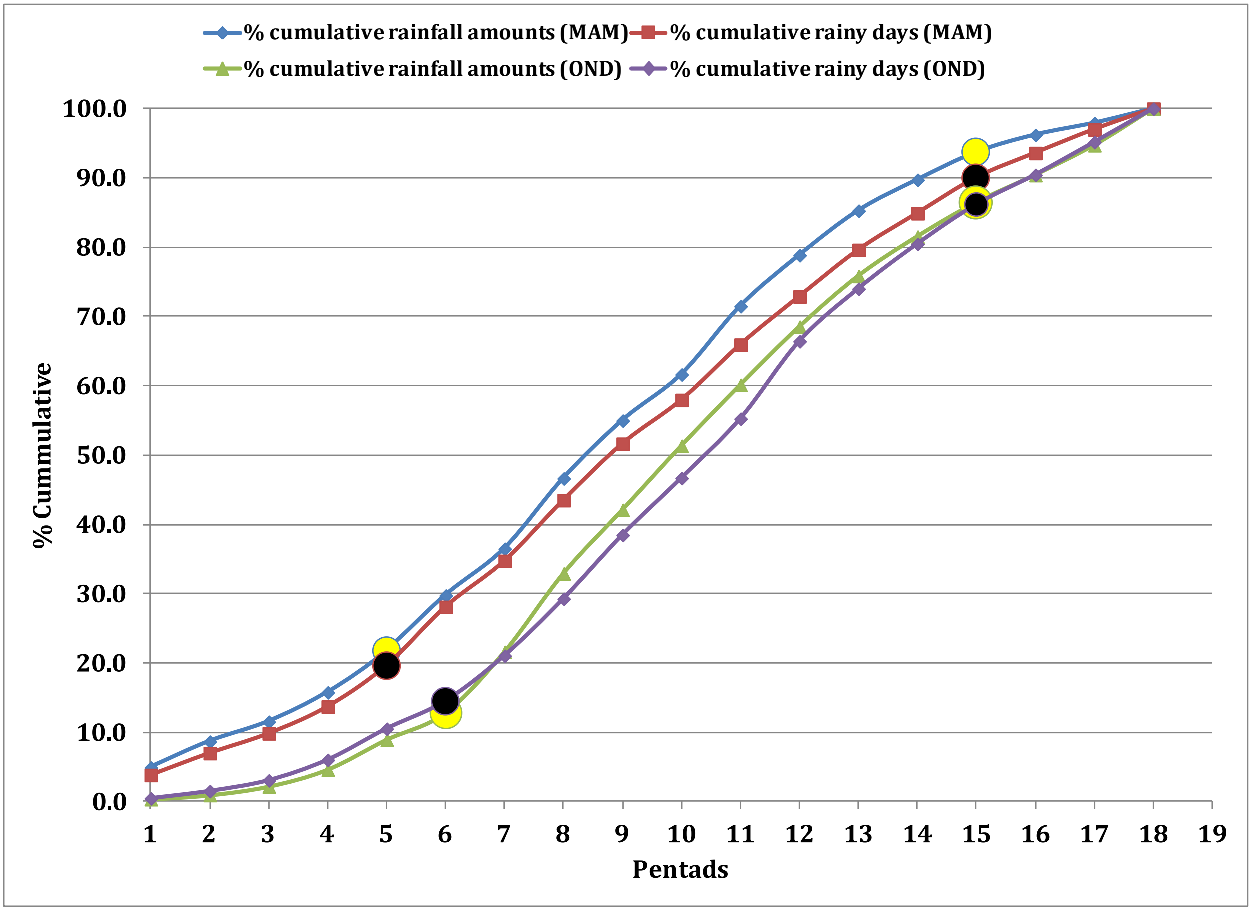

Figure 8: Cumulative percentages of rainfall amounts and number of rainy days for Katumani Meteorological station during the MAM and OND seasons. The yellow and black circles represent the cumulative percentages of rainfall amounts and rainy days, respectively

4.2.2 Variation in the Monthly, Seasonal and Annual Rainfall Amounts

Monthly analysis of rainfall amounts for all the three stations (Katumani, Iveti and Machakos D.O) indicates that during both rainfall seasons, the first and last months are denoted by high variability compared to the peak months (April and November) (Table 10). Comparable results were reported in Recha *et al*. (2011) in which onset (March and October) and cessation (May and December) months are characterized by variations greater than the mid seasonal months (April and November) in Tharaka district, Kenya. These results are also consistent with Sivakumar (1987) in Sudano-Sahelian zone.

In addition, rainfall received during the seasonal peak months of April and November accounted for approximately 50% of the MAM seasonal rainfall totals at the three stations considered in this study (Table 10).

Approximately 28% and 16.5% of the total seasonal rainfall in the three (3) meteorological stations is received in the months of onset (March and October). On the other hand, the cessation months (May and December) accounts for approximately 20% and 33% of the seasonal rainfall totals (Table 10). For MAM season, the cessation month (May), accounts for approximately 20% of the total rainfall whereas, the cessation month during the OND season (December), accounts for approximately 33% of the total rainfall (Table 10). The findings of this study are in conformity with Recha *et al*. (2011) where the cessation of OND season (December) accounted for greater percentage as compared to May the cessation month of MAM season. The results indicate that the OND seasonal rainfall amount is fairly well distributed throughout the three months of season, thus having the capacity to reduce the impact of variation of rainfall amounts within the season at 16.5%, 50% and 33%, hence minimizing the effect of within season variability. Less amount of rainfall is received in May and might not be adequate for crop production in case of a drought event within the county where the water holding capacity of the crusting sandy clay loams is low.

Analysis of seasonal rainfall amounts (Table 10) indicates that Iveti and Katumani receive more rainfall during the OND season. However, for Katumani the difference in rainfall amounts during the two seasons was not statistically significant. These findings agree with those of Amissah-Arthur *et al*. (2002), Barron *et al*. (2003) and Njiru *et al*. (2010)) which showed that some regions in Eastern Kenya receive more rainfall during the OND season than MAM season. On the other hand, Machakos D.O station recorded slightly more rainfall during MAM than OND season. Therefore, because OND is the major season in Machakos County, farmers should plant early maturing sorghum cultivars during MAM so as to avoid the risk of crop failure

Considering the three stations in the study both MAM and OND seasonal rainfall had their coefficient of variation exceeding 30%. According to Araya and Stroosnijder (2011) and Hare (1983) a CV greater than 30% indicates higher variability of the parameter. However, the MAM season had slightly higher variability compared to the OND season (Table 10). This study results are consistent with other analysis (Mutai and Ward, 2000) where MAM seasonal rainfall variability in East Africa region is higher than OND seasonal rainfall. However, the results disagree with those of Recha *et al*. (2011) who found out that in Tharaka District (semi-arid parts of Eastern Kenya) that the MAM seasonal rainfall was less variable than the OND seasonal rainfall.

In the study area the mean annual rainfall was 1035.5mm, 816.6mm and 699.1mm for Iveti, Machakos D.O and Katumani stations, respectively. The highest amount of rainfall recorded at Iveti could be attributed to the higher amounts of seasonal rainfall received at the station and the fact that Iveti is a highland while the other stations are lowlands. The annual variability was higher at Iveti and Machakos D.O stations (39.2% and 36.7%), while for Katumani the variability was moderate (26.3%)

Table 10: Mean monthly, seasonal and annual rainfall totals (RT), their respective coefficient of variation (CV) and percentage proportion for the three stations used for the period 1981 to 2012

Stations	Parameter	March	April	May	October	November	December	MAM	OND	Annual
Iveti	RT	119.4	191.8	83.9	92.1	255.4	156.9	395.1	504.5	1035.5
	CV (%)	78.2	67.9	91.5	104.1	53.3	59.1	56.5	52.6	39.2
	Proportion (%)	30.2	48.5	21.2	18.2	50.6	31.1	38.2	48.7	
Machakos D.O	RT	79.4	195.6	69.7	54.6	172.9	115.4	344.7	342.9	816.6
	CV (%)	75.6	71.5	94.5	90.2	58.2	73.7	57.8	51.6	36.7
	Proportion (%)	23.0	56.7	20.2	15.9	50.4	33.6	42.5	41.9	
Katumani	RT	86.7	133.4	55.0	43.4	143.6	94.6	272.1	279.6	699.1
	CV (%)	70.9	45.5	79.1	87.3	59.8	85.6	44.5	44.2	26.3
	Proportion (%)	31.8	49.2	20.2	15.5	51.3	34.7	38.9	40.1	

4.2.3 Variation in the Seasonal and Annual Temperature

During the MAM season the mean maximum and minimum temperatures were higher compared to the OND and annual, with values ranging from 25.9 ± 0.6 and 14.5 ± 0.5, respectively (Table 11). Both maximum and minimum temperature depicted less variability (<5%) at both seasonal and annual timescales. However, variation in maximum temperature was less compared to that of minimum temperature.

Comparing the variability of rainfall and temperature, rainfall characteristics showed greater variability while temperature depicted less variation both at seasonal and annual scale. This indicates that both maximum and minimum temperatures are almost stable in each season and year.

Table 11: Descriptive statistics of seasonal and annual temperature and annual sorghum yield over Machakos County

Parameter	**Descriptive Statistics**	**Seasonal**		**Annual**
		MAM	**OND**	
Tmax	**Maximum**	27.0	26.2	25.9
	Minimum	24.7	24.2	24.0
	Mean	25.9	25.2	25.1
	CV	2.3%	1.9%	1.5%
Tmin	**Maximum**	15.3	15.3	14.1
	Minimum	12.9	13.1	12.3
	Mean	14.5	14.2	13.3
	CV	3.4%	3.5%	3.0%
Sorghum yield	**Maximum**			0.97t/ha
	Minimum			0.05t/ha
	Mean			0.5t/ha
	CV			45%

4.2.4 Variation in the Sorghum Yields

The variability of annual sorghum yield was 45% (Table 11); this value denoted larger variability of annual sorghum yield in the area of study, thus increasing the risk to farmers.

4.2.5 Trends in Climate Variables

The analysis of trends on the intra-seasonal rainfall characteristics, seasonal and annual series of rainfall, minimum and maximum temperature were obtained by both Mann Kendall and linear regression analysis.

4.2.5.1 Trend Analysis of Intra-Seasonal Rainfall Characteristics

During the study period, decreasing trends in the onset and cessation dates were observed during the MAM and OND season, depicting early onsets and early cessations an indication that the seasons were shifting backwards (Figure 9 and Table 12). However, the observed trends in the intra- seasonal rainfall characteristics were statistically insignificant (Table 12).

On the other hand, the duration for both seasons and number of rainy days during the OND season depicted an insignificant increasing trend. An increasing trend in the duration and rainy days during the OND season indicates the suitability of the season for rain-fed agriculture within the study area owing to enhanced soil moisture content for longer duration hence resulting to better yields.

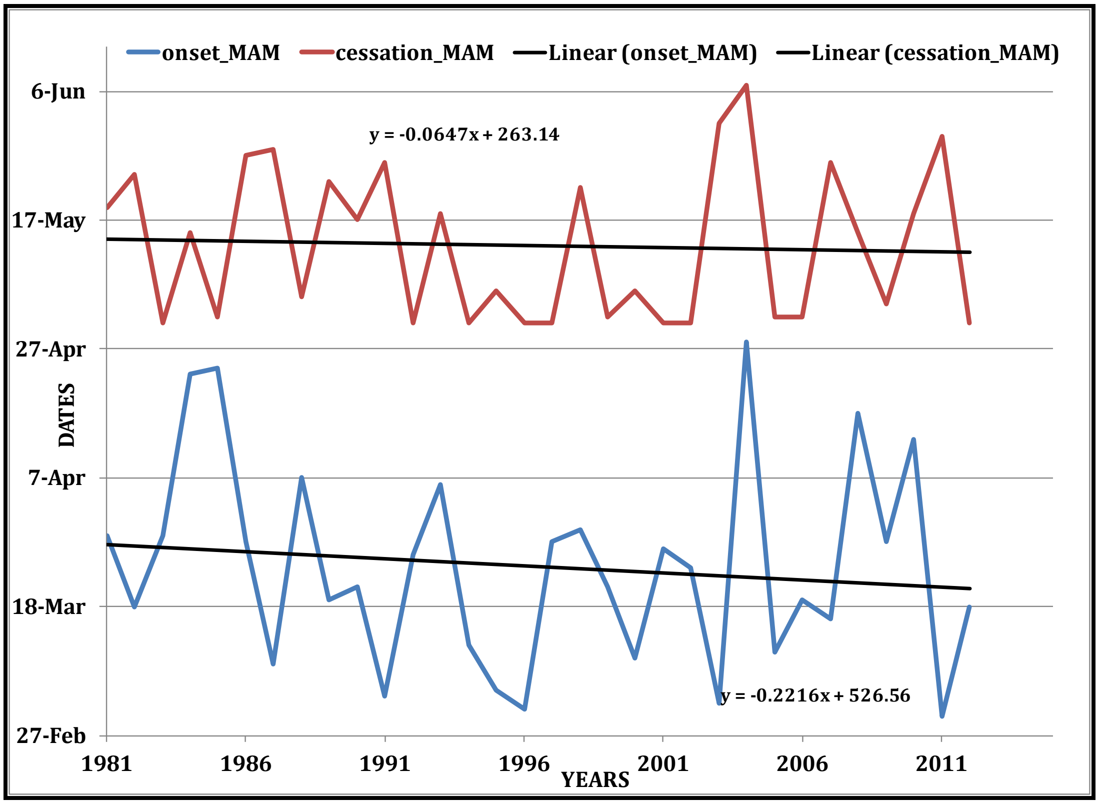

Figure 9: Trends for onset and cessation during the MAM season for the period 1981 to 2012

Table 12: Observed trends in the MAM and OND intra-seasonal rainfall characteristics at Katumani

Season	**Parameter**	**Mann-Kendall**		**a**
		tau	***p-value***	
MAM	Onset	-0.16	0.16	-0.22
	Cessation	-0.09	0.45	-0.06
	Duration	0.03	0.81	0.17
	Number of rainy days	-0.02	0.80	-0.05
OND	Onset	-0.08	0.49	-0.21
	Cessation	-0.06	0.58	-0.06
	Duration	0.06	0.57	0.15
	Number of rainy days	0.07	0.51	0.07

a: Slope of linear regression (days/year), tau: Mann-Kendall test statistic

4.2.5.2 Trend Analysis of Seasonal and Annual Rainfall

The trends of seasonal and annual rainfall and their magnitudes for three weather stations (Iveti, Machakos DO and Katumani) for the period 1981-2012 obtained by the Mann-Kendall and the linear regression analysis are shown in Table 13. During the MAM season, the trend test detected a significant and insignificant decreasing trend at Machakos DO and Iveti stations, respectively. On the contrary, Katumani was characterized by a slight positive trend, which was not statistically significant (Table 13). The trend tests identified a statistically significant declining trend in the OND seasonal rainfall for both Iveti and Machakos DO (Table 13). The rate of change of the significant decreasing trend during the OND season ranged between (-) 14.06 and (-) 8.1mm per year at Iveti and Machakos DO, respectively (Figure 10).

Generally the OND seasonal rainfall depicted declining trends within the study area. The findings of this study agree with Njiru *et al*. (2010) where the OND seasonal rainfall revealed a decreasing trend in Katumani. However, the results are contrary to other seasonal analysis (Shisanya *et al*., 2011; Schreck and Semazzi, 2004) where the OND seasonal rainfall depicted a slight positive trend in parts of the ASALs of Kenya. These contradicting results could be attributed to the methods of analysis used whether parametric or non-parametric, length of the data sets, whether the data was gridded or point observation and the area of study. Thus there is need for performing location specific analyses of rainfall trends to ascertain arguable affirmations on the same. Amissah-Arthur *et al.* (2002) and Hansen and Indeje (2004) suggested that in Eastern parts of Kenya, OND seasonal rainfall corresponds to the major growing season on which most annual crops are reliant on. Hence, its decrease has repercussions on agricultural production and associated livelihoods.

Analysis of annual rainfall revealed a decreasing trend in all the stations. However, the trends were only statistically significant for Iveti and Machakos DO stations (Table 13). The study findings are consistent with other previous studies conducted in the ASALs of Kenya where the trends in the annual rainfall were decreasing significantly (Shisanya *et al*., 2011; Omoyo, 2015).

The significant observed decreasing trends in the OND seasonal rainfall and annual rainfall at Iveti and Machakos D.O imply that OND seasonal rainfall is a considerable factor determining variability of annual rainfall in the County.

Table 13: Observed trends for the seasonal and annual rainfall over the period 1981 to 2012. The bold values represent statistically significant trends at 95% confidence level

Parameter		**Station**		
		Katumani	**Iveti**	**Machakos DO**
MAM Rainfall				
Mann Kendall	tau	0.08	-0.21	**-0.33**
	p-value	0.55	0.09	**0.008**
Linear Regression	a	1.43	-8.98	**10.21**
OND Rainfall				
Mann Kendall	tau	-0.088	**-0.36**	**-0.379**
	p-value	0.53	**0.003**	**0.024**
Linear Regression	a	-1.66	**-14.06**	**-8.11**
Annual Rainfall				
Mann Kendall	tau	-0.02	**-0.38**	**-0.427**
	p-value	0.91	**0.002**	**0.0006**
Linear Regression	a	-1.23	**-24.09**	**-18.99**

a: Slope of linear regression (mm/year), tau: Mann-Kendall test statistic

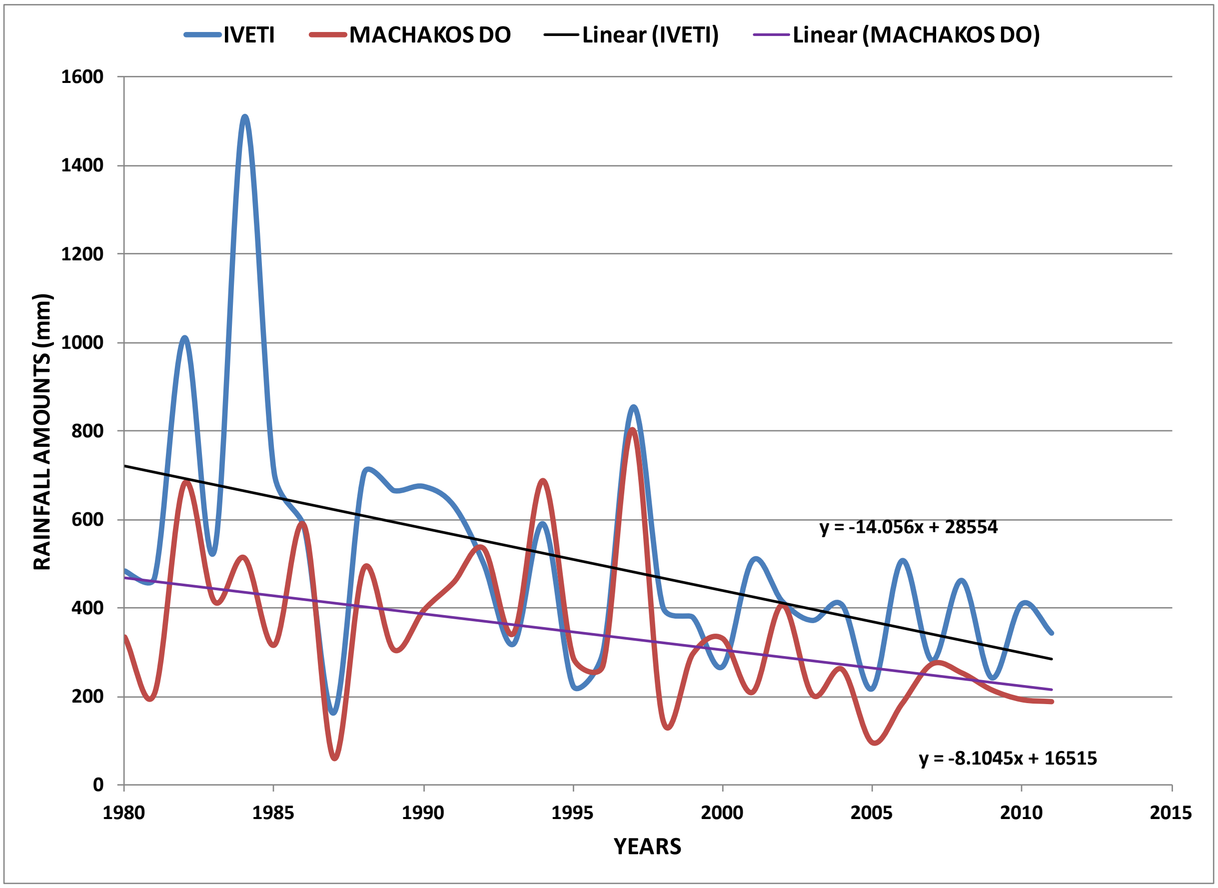

Figure 10: Trends for OND seasonal rainfall at Iveti and Machakos DO for the period 1981 to 2012

4.2.5.3 Trend Analysis of Maximum and Minimum Temperature

The results of the trend analysis for the seasonal and annual maximum and minimum temperature (TMax and TMin) for Katumani station are presented in Table 14. From these results both seasonal maximum and minimum temperature exhibited increasing trends. This affirmation can be compared with other studies by Schreck and Semazzi (2004) in the GHA region that emphasized a general warming trend. The results are also similar to those by Collins (2011) where seasonal maximum temperature exhibited a rapid warming in Kenya.

The positive trends for maximum and minimum temperature were statistically significant during the OND and MAM season, respectively (Table 14). Based on the slopes of the linear regression lines the rate of increase of OND maximum and MAM minimum temperatures were (+) 0.03 and (+) 0.04 ° C per year, respectively.

The trend test showed statistically significant increasing trend in annual maximum and minimum temperature. This indicates a warming trend in the annual temperatures. These findings are consistent with other previous studies which discovered increasing trend in the annual maximum temperature in Katumani (Njiru *et al*., 2010). The rate at which the annual maximum and minimum temperature increased was (+) 0.04°C and (+) 0.03°C per year, respectively.

Such warming trends of temperature are likely to result in the increase in the rate of photosynthesis, which sequentially enhances sorghum growth and development. On the other hand, warming reduces the sorghum growth cycle provided that other vital factors are not limiting. The reduction in the growth duration will require farmers within the County to shift from planting long duration to short maturing sorghum cultivars, whose grain yield potential is low (Wylie, 2008).

Table 14: Observed trends for the seasonal and annual maximum and minimum temperature for Katumani over the period 1981-2012. The bold values represent statistically significant trends at 95% confidence level

Parameter	Statistical Test	Seasons		Annual
		MAM	**OND**	
Tmax	**Tau**	0.10	**0.33**	**0.41**
	p-value	0.53	**0.02**	**0.01**
	a	0.02	**0.03**	**0.04**
Tmin	**Tau**	**0.35**	0.27	**0.04**
	p-value	**0.02**	0.07	**0.01**
	a	**0.04**	0.03	**0.03**

a: Slope of linear regression (°C/year), tau: Mann-Kendall test statistic

4.2.6 Trend in Sorghum yield

From Mann-Kendall test statistic the value of tau was 0.22 and the p-value was 0.11. This clearly indicated that though the trend was increasing it was statistically insignificant. The magnitude of the increasing trend was at the rate of 0.004 tonnes/ha/year (Figure 11).

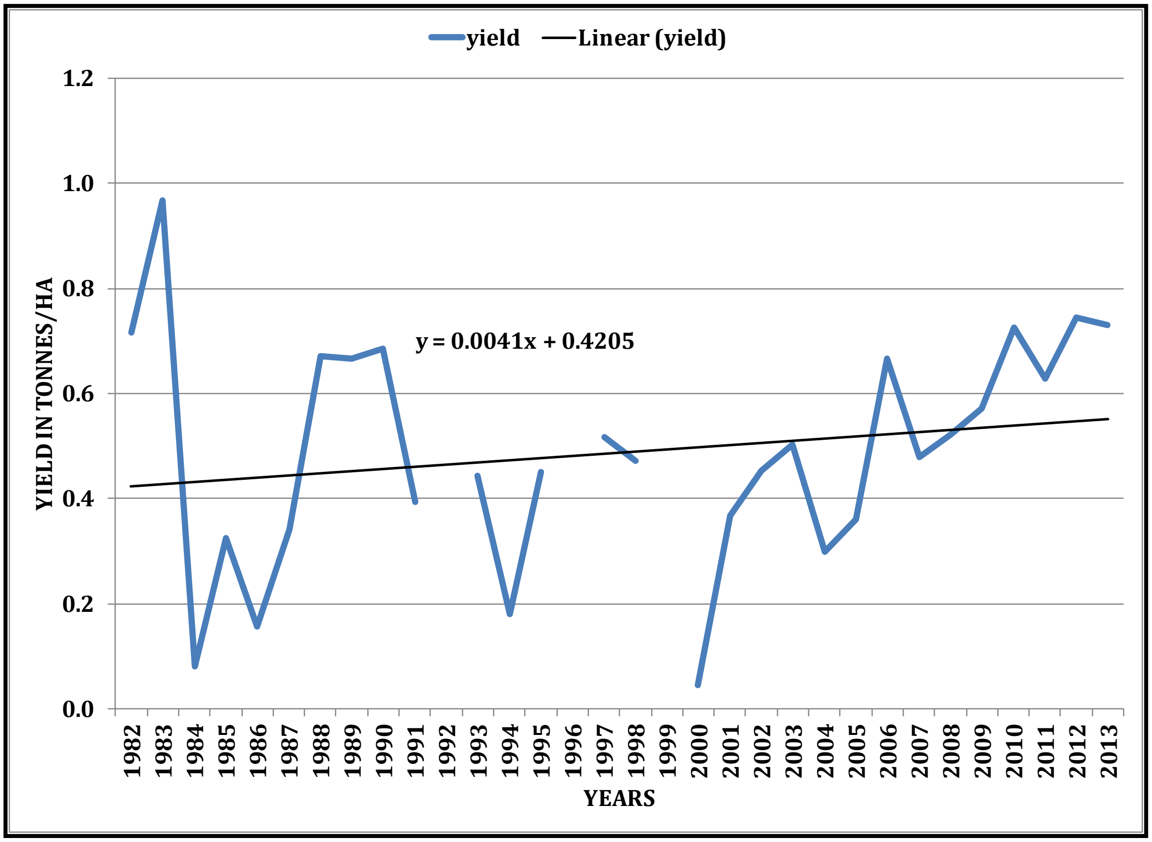

Figure 11: Time series for annual sorghum yield in Machakos County for the period 1982 to 2013

4.2.7 Response of Sorghum Yield to Climate Elements

The result of the correlation between the climatic elements and sorghum yield in Machakos County are presented in Table 15. The results show differences in the effect of each element on sorghum yield at different phenological phases.

During the vegetative phase (germinating and seedling establishment phase), MAM seasonal rainfall depicted positive and significant correlation coefficient with sorghum yield. This shows that rainfall supply during vegetative phase is important for increased sorghum yield in Machakos County during the MAM growing season. However, the OND seasonal rainfall showed a positive insignificant correlation coefficient. Both maximum and minimum temperature showed negative significant correlation coefficient with the final sorghum yield, during the OND growing season. This could be attributed to the fact that very cold temperatures during vegetative phase results to reduced germination by inhibiting seedling growth and thus affecting stand establishment. This will lead to low plant population and hence results to reduction in sorghum yield (Yu *et al*., 2001; Franks *et al*., 2006).

During the reproductive phase (flowering and seed setting phase), MAM seasonal rainfall and maximum temperature showed positive and negative significant correlation, respectively. The attribution is that the reproductive phase is susceptible to water stress and that the water requirement during this phase increases gradually. Water deficit during flowering period affects pollen development and viability. This could perturb fertilization and seed development leading to poor seed setting, thus resulting to decrease in the final yield (Barnabas *et al*., 2008). On the other hand, very high temperature beyond the optimum delays panicle emergence or even complete panicle inhibition.

During maturity phase (grain filling phase), MAM seasonal rainfall showed positive and significant correlation coefficient. However, the value was relatively lower as compared to that of the reproductive phase. This could be attributed to the gradual decrease of the overall water requirement during maturity phase due to lesser evaporative demand, reduced transpiration rates owing to leaf senescence and modification in plant physiology.

For the total growing season, seven parameters were tested during both MAM and OND growing seasons. During the MAM growing season rainfall and the number of rainy days depicted positive significant correlation coefficient. This indicates that high amounts of rainfall and increased number of rainy days during the MAM season is an indicator of increase in the sorghum yields. During the OND growing season; cessation dates, duration of the seasonal rainfall and rainy days showed positive significant correlation coefficient. This indicates longer cessation dates, and higher number of rainy days during the OND season is an indicator of increase in the sorghum yields.

During the OND growing season, the positive insignificant correlation coefficients of the, rainfall and sorghum yield during the vegetative, reproductive, maturity and the total growing season indicates that rainfall is a crucial element influencing the yield of sorghum. However, during the MAM growing season, positive insignificant correlation coefficients of the onset dates, cessation dates and duration clearly indicates that these seasonal rainfall characteristics are important elements influencing the final yield of sorghum.

4.2.8 Combined Effects of Climatic Elements on Sorghum Yield

Results of the correlation analysis discussed above (section 4.2.7) simply presented the isolated association between the climatic parameters and sorghum yield. Correlation analysis does not specify the level of influence of that climatic parameter on the sorghum yield. So as to clearly identify those climatic parameters that are important to sorghum production, the thirteen (13) climatic parameters that had contributed significantly during the growth stages of sorghum were additionally subjected to step-wise regression analysis.

Table 16, displays the result of the step-wise regression analysis. Four (4) out of the thirteen (13) climatic parameters considered significantly contributed to the variation in sorghum yield in Machakos County.

These observed climatic parameters are total rainfall during the MAM growing season, minimum temperature for the vegetative phase during the OND season, duration of rainfall during the OND season and rainy days during OND growing season. In the regression model, the four parameters collectively accounted for 90.5% of the total variance in the yield of sorghum in Machakos County.

Table 15: Correlation Matrix of climatic elements with sorghum yield at various phenological phases, the bold and bold italic character represents positive and negative significant coefficients, respectively

Season	**Climatic Element**	**Vegetative Phase**	**Reproductive Phase**	**Maturity Phase**	**Total Growing season**
March-May	Rainfall (mm)	**0.55**	**0.47**	**0.37**	**0.35**
	Maximum Temperature (°C)	-0.19	***-0.45***	***-0.39***	-0.10
	Minimum Temperature (°C)	0.30	0.02	-0.18	0.10
	Onset dates of rainfall				0.21
	Cessation dates of rainfall				0.17
	Duration of the season				0.22
	Number of rainy days				**0.49**
October-December	Rainfall (mm)	0.07	0.18	0.26	0.24
	Maximum Temperature (°C)	***-0.42***	-0.34	**0.56**	-0.20
	Minimum Temperature (°C)	***-0.49***	-0.12	0.33	0.20
	Onset dates of rainfall				-0.32
	Cessation dates of rainfall				**0.41**
	Duration of the season				**0.44**
	Number of rainy days				**0.35**

Table 16: Summary of Step-wise Regression Analysis

Parameter	**Coefficient**	**Std Error**	**t**	**P(2 Tail)**
Constant	158893.559	68667.216	2.314	0.041
Total rainfall during the MAM growing season	101.165	19.038	5.314	0.000
Minimum temperature for the vegetative phase during the OND season	-15049.653	5043.408	-2.984	0.012
Duration of rainfall during the OND season	219.876	35.983	6.110	0.000
Number of rainy days during OND growing season	619.009	153.930	4.021	0.002

Analysis of Variance

Source	Sum of Squares	df	Mean Square	F-ratio	p
Regression	3.11421E+09	4	7.78553E+08	26.170	0.000
Residual	3.27245E+08	11	2.97496E+07		

The P values in Table 16 show that each of the parameters used has a statistically significant predictive potential in the presence of the other parameters, to be precise; each parameter adds value to the regression equation. There is less probability that the actual value of the parameters being estimated could be zero; implying that if the term of the regression equation containing the parameter are eliminated the accuracy of the regression will be affected significantly.

The overall significance of the regression model was tested using the F-ratio and its P-value. The P-value for the F-test was less than the significance level, therefore the null-hypothesis (all coefficients of regression equation were equal to zero) was rejected and it was concluded that the regression equation obtained had some validity in fitting the data.

4.3 Field Experimental Results

4.3.1 Environmental Conditions

The two cropping seasons in 2014 and 2015 had different weather conditions. Rainfall, Maximum temperatures, minimum temperatures, and solar radiation during growing season (from April to August and from October to February) and their long term means are presented in Table 17 and Table 18.

Table 17: Monthly mean weather conditions during crop growth seasons April to August 2014 and 2015

	Maximum Temperature (°C)			**Minimum Temperature (°C)**			**Radiation (MJ m^{-2} day^{-1})**			**Rainfall Totals (mm)**		
Month	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**
April	25.3	26.4	25.7	15.2	16.1	15.0	18.4	18.7	23.7	44.0	95.2	136.1
May	25.2	24.9	24.7	14.5	15.2	14.1	17.8	16.9	21.3	15.3	31.5	53.3
June	24.1	24.6	23.6	13.2	15.1	12.2	17.1	16.1	19.2	9.7	9.9	8.3
July	23.5	24.1	22.6	12.4	12.5	10.9	17.5	18.5	17.5	13 .0	5.4	3.5
August	24.5	24.0	23.2	12.8	12.2	11.6	19.1	19.2	18.3	32.4	1.2	5.8
Mean/Total	24.5	24.8	24.0	13.6	14.2	12.8	18.0	17.8	20.0	114.4	143.2	207

Table 18: Monthly mean weather conditions during crop growth seasons October to February 2014 and 2015

	Maximum Temperature (°C)			**Minimum Temperature (°C)**			**Radiation (MJ m^{-2} day^{-1})**			**Rainfall Totals (mm)**		
Month	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**	**2014**	**2015**	**LTM**
October	28.1	27.3	26.9	15.1	15.4	13.9	21.6	20.7	23.8	29.3	10.4	36.2
November	25.4	25.0	24.6	15.5	15.7	14.8	18.5	17.9	22.5	104.8	274.9	176.5
December	24.9	24.8	24.6	14.7	15.2	14.3	18.5	17.9	23.5	41.6	222.4	113.6
January	27.9	25.8	26.1	13.7	15.2	13.5	22.1	19.1	25.3	1.5	30.6	61.5
February	28.8	26.8	27.7	14.6	14.0	13.7	22.6	21.5	26.9	68.9	25.4	37.6
Mean/Total	27.0	26.0	26.0	14.7	15.1	14.0	20.7	19.4	24.4	246.1	563.7	425.4

(°C): Degrees Celsius, (MJ m^{-2} day^{-1}): Mega joules per square meter per day, mm: millimeters and LTM: Long term mean

4.3.1.1 Maximum and Minimum Temperature

Temperatures patterns during the long rainfall growing period (April to August growing season), 2014 (2015) were fairly similar, with the average maximum and minimum temperatures of 24.5°C (24.8°C) and 13.6°C (14.2°C), respectively compared to mean maximum and minimum temperature of 24.0°C and 12.8 °C for the long term average (1981 to 2012). In both years, both average maximum and minimum temperature were slightly above long-term average. The lowest maximum temperature of 23.5°C (24.0°C) for the long rainfall growing period 2014 (2015) was recorded in the month of July (August) with its highest maximum temperature of 25.3°C (26.4°C) occurring in the month of April (Table 17). The least minimum temperature of 12.4°C (12.2°C) for the long rainfall growing period 2014 (2015) was recorded in the month of July (August) with its highest minimum temperature of 15.2°C (16.1°C) occurring in the month of April (Table 17).

The average of both maximum and minimum temperatures for the short rainfall growing period (October to February growing season), 2014 (2015) were 27.0°C (26.0°C) and 14.7°C (15.1°C), respectively compared to mean maximum and minimum and of 26.0°C and 14.0°C for the long term average. The lowest maximum temperature of 24.9°C (24.8°C) for the short rainfall growing period 2014 (2015) was recorded in the month of December with its highest maximum temperature of 28.8°C (27.3°C) occurring in the month of February (October) (Table 18). The least minimum temperature of 13.7°C (14.0°C) for the short rainfall growing period 2014 (2015) was recorded in the month of January (February) with its highest minimum temperature of 15.5°C (15.7°C) occurring in the month of November (Table 18).

Optimal temperature range for sorghum at vegetative phase is between 26 to 34°C (Hammer *et al*., 1993) and that during the reproductive phase is between 25 to 28°C (Prasad *et al*., 2006). The observed temperatures during the growing season were slightly out of but within the optimum ranges during the vegetative phase and reproductive phase for April to August growing season. Therefore sorghum could have relatively performed well in the area of study during the April to August growing season. However, the temperatures were within the optimum ranges during the October to February growing seasons as suggested by Hammer *et al*., 1993 and Prasad *et al*., 2006, hence sorghum could perform better in the area of study during these seasons compared to the April to August growing seasons. Increase in temperature beyond the optimum range result in withering of the sorghum plants as a result of the scorching effect of the sun.

4.3.1.2 Solar Radiation

The average daily solar radiation for the long rainfall growing period (April to August growing season), 2014 and 2015 was 18.0 $MJm^{-2}day^{-1}$ and 17.8 $MJm^{-2}day^{-1}$ compared to the long term average (1981 to 2012) of 20.0 $MJm^{-2}day^{-1}$ (Table 17). The least solar radiation (17.1 and 16.1 $MJm^{-2}day^{-1}$) for the long rainfall growing period 2014 and 2015 was recorded in the month of June with the highest solar radiation (19.1 and 19.2 $MJm^{-2}day^{-1}$) occurring in August, respectively (Table 17).

The least (maximum) value of solar radiation in June (August) corresponds to the periods of attainment of flowering (Maturity), hence low (high) evaporation demands is necessary for the crop to attain maximum yields. Decreasing values of solar radiation from planting to flowering allows for little evaporation to take place, thus preventing the issue of water stress during this critical period. Conversely, increasing solar radiation trends from flowering to maturity allows for rapid evaporation thus the grain sorghum ripens quickly.

On the other hand, the average daily solar radiation for the short rainfall growing period (October to February growing season), 2014 and 2015 was 20.7 $MJm^{-2}day^{-1}$ and 19.4 $MJm^{-2}day^{-1}$ compared to long term average (1985-2015) of 24.4 $MJm^{-2}day^{-1}$ (Table 18). The least solar radiation (18.5 and 17.9 $MJm^{-2}day^{-1}$) for the April to August growing season 2014 and 2015 was recorded in the months of November/December with the highest solar radiation (22.6 and 21.5 $MJm^{-2}day^{-1}$) occurring in February, respectively (Table 18).

The least (maximum) value of solar radiation in November/December (February) corresponds to the periods of attainment of flowering (Maturity), hence low (high) evaporation demands is necessary for the crop to attain maximum yields. Decreasing values of solar radiation from planting to flowering allows for little evaporation to take place, thus preventing the issue of water stress during this critical period. Conversely, increasing solar radiation trends from flowering to maturity allows for rapid evaporation thus the grain sorghum ripens quickly.

4.3.1.3 Rainfall

In disparity to the comparable temperature patterns, distribution of rainfall was different during the two years. The total rainfall for long rainfall growing period (April to August growing season), during 2014 and 2015 were 114.4mm 143.2mm, respectively. These rainfall amounts were below the long-term average (1981 to 2012) of 207.1mm (Table 17). Compared to the long term mean the two seasons had received less rainfall. The total rainfall received during the long rainfall growing period 2014 and 2015 were 44.7% and 30.8% lesser than the long term mean (1981 to 2012).

The total rainfall received in the month of April 2014 and 2015 were 44.0mm and 95.2mm which were 67.6 % and 30.1% lower than the long-term mean of 136.1 mm for April (Table 17). This low rainfall amounts corresponded with the start of planting and this deprived the soil from enough moisture necessary for germination and seedling establishment. The water requirement for sorghum at vegetative phase is 1 to 2.5 mm/day (Stichler and Fipps, 2003).

The months that corresponded to the time of planting until flowering during the growing seasons of April to August 2014 and 2015 accumulated rainfall amounting to 69mm and 136.6mm, respectively. The rainfall amounts were approximately 65.1% and 31% below the long term mean respectively in 2014 and 2015 (Table 17). The rainfall amounts during 2015 were seen to be favorable for better sorghum growth since the crop water requirement increases during the reproductive phase (7 to 1omm/day, according to Stichler and Fipps, 2003).

The total rainfall in the month of August for 2014 and 2015 were 458.6 % greater and 79.3% less than the long-term mean (Table 17). Too much rainfall received in August 2014 resulted in adverse effects on sorghum growth and development and hence reduced the grain quality. This attributed to the lower yields attained during the long rainfall growing period in 2014 as compared to 2015.

The total rainfall for the short rainfall growing period (October to February) 2014 and 2015 was 246.1mm 563.7mm, respectively. The long term mean (1981 to 2012) was found to be 425.4mm. In 2014 short rainfall growing period, rainfall amount recorded was below the long-term mean. During the short rains of 2015, total rainfall was higher than the long-term mean, and approximately 317.6 mm additional rain was recorded in 2015 (Table 18).

From planting to flowering, the rainfall amount received in 2014 and 2015 was 175.7mm and 507.7mm, respectively, in comparison to the long term mean of 290.1mm. Water requirement for sorghum growth and development increases from planting to flowering and thereafter the water requirements decreases during grain filling until the crop matures (Stichler and Fipps, 2003). Hence, the higher amounts of rainfall received during October to December in 2015 contributed to higher yields compared to 2014. The relatively higher amounts of rainfall (68.9mm) received in February 2014 (Table 18) during the short rainfall growing period could have resulted in poor yields since that month corresponded to the month of harvesting. Heavy rainfall during harvesting is known to affect the grain quality by resulting to rotting of the grains.

Generally rainfall distribution for the two seasons in 2014 and 2015 signify the ongoing rainfall variability which strongly influences growth and development of sorghum and thus led to the variability in the sorghum yield that were obtained from the four experimental seasons.

4.3.2 Initial Soil Properties

The soil profile samples were obtained from four layers (0-15cm, 15-30cm, 30-60cm and 60-90cm). Table 19 gives an overview of the physical and chemical attributes of soils at Katumani Research station in 2014.

The soils in Katumani are sandy clay in all the layers. The soil profile depicted a decreasing trend in the bulk density. A decreasing trend in the bulk density is more beneficial to the growth of plants (Rowell, 1994) because of high porosity. DUL and LL15 showed a decreasing trend in the 1st two layers then an upward trend in the subsequent layers. Air dry and SAT depicted an increasing trend throughout the layers (Table 19).

The pH of the soil was slightly acidic with pH ranging between 6.0 and 6.5. The average Organic Carbon and total Nitrogen in the soil was 0.85% and 0.065%. The general rating of soils containing organic carbon is as follows > 20 % very high, 10 to 20 % high, 4 to 10 % medium, 2 to 4 % low and < 2 % very low (Landon, 1996). On the other hand, the description of the percentage total Nitrogen content in soil is as follows > 1.0 very high, 0.5 – 1.0 % high, 0.2– 0.5 % medium, 0.1 – 0.2 % low and < 0.1 very low (Landon, 1996). In reference to these ratings, the percentage of both Organic Carbon and total Nitrogen from the study area could be described as very low. The very low levels of Nitrogen levels in the soil could be ascribed to very low Organic Carbon levels depicted in the study area. The same observation could also be partially attributed to leaching and volatilization which results in Nitrogen losses.

Table 19: Pre-planting soil characteristics at Katumani research station in 2014

Soil Depth (cm)	**0-15**	**15-30**	**30-60**	**60-90**	**Ratings**
Particle size distribution (%)					
Sand	68	69	62.5	50.5	-
Clay	25.3	23.5	31.5	40	-
Silt	6.7	7.5	6.0	9.5	-
Bulk Density (g/cc)	1.57	1.57	1.55	1.51	Ideal
DUL (mm/mm)	0.24	0.23	0.30	0.35	-
Air Dry (mm/mm)	0.10	0.11	0.20	0.24	-
LL15 (mm/mm)	0.16	0.15	0.20	0.24	-
SAT (mm/mm)	0.34	0.34	0.37	0.38	-
Sorghum LL (mm/mm)	0.16	0.15	0.20	0.27	-
Soil pH (1:5 water)	6.5	6.5	6.2	6.0	Slightly acidic
Exchangeable Cations (cmol(+)/kg					
Calcium	3.5	4.1	2.3	2.1	Very high
Magnesium	6.6	6.2	6.1	5.9	Very high
Sodium	0.3	0.3	0.2	0.2	Low
Potassium	0.9	0.8	0.7	0.4	High
% Organic Carbon	0.9	0.8	1.0	0.7	Very low
% Total Nitrogen	0.08	0.07	0.06	0.05	Very low
NO_3^- **N***(kg/ha)*	13.44	9.53	10.05	3.93	-
NH_4^+ **N***(kg/ha)*	1.92	0.19	0.40	0.39	-
Fbiom	0.035	0.020	0.015	0.010	-
Finert	0.390	0.470	0.520	0.620	-

DUL: Drained Upper Limit (Field capacity), Air Dry: Soil moisture content at air dry point, LL15: Lower Limit of water extraction by the crop at 15 bar metric pressure (Wilting Point), SAT: saturated volumetric water content, NH_4^+N*: Ammonium nitrogen,* NO_3^-N*: Nitrate nitrogen, Fbiom: fraction of soil organic matter that is decomposable and originally present in the fast decomposing pool, Finert: fraction of soil carbon which is not vulnerable to decomposition*

The exchangeable cations of the soils within the study area were also recorded. The average values obtained were 3, 6.2, 0.25 and 0.7 cmol(+)kg^{-1} for Calcium, Magnesium, Sodium and Potassium, respectively. Calcium content < 0.2 is rated very low, 0.2-0.5 low, 0.6-2.5 moderate, 2.6-5.0 high and > 5.0 very high. Magnesium content < 0.2 is rated very low, 0.2 − 0.5, 0.5-1.0 moderate, 1-2 high and >2 very high. Based on these ratings the soils in the study area have high and very high Calcium and Magnesium contents, respectively. The rating of soils containing sodium cations is as follows < 0.1 very low, 0.1-0.3 low, 0.3-0.7 moderate, 0.7-2 high and > 2 very high. Potassium content is rated as <0.05 very low, 0.05-0.1 low, 0.1-0.4 moderate, 0.4-0.7 high > 0.7 very high. Basing our results on these ratings the soils at Katumani have low and high sodium and potassium, respectively. Situations where by the estimated Sodium cations exceeds 1.0 cmol(+)kg^{-1} the soil is considered "sodic" and this has an impact on the yield of most cereals.

Owing to low content in organic carbon and the sandy characteristics of the soils, water infiltration is high resulting to poor water holding capacity. This is not favorable for crop production, particularly in this study area which is known to have low and irregular rainfall with frequent dry spells.

4.3.3 Effect of Temperature on Sorghum Growth and Development

Tables 20 and 21, display the Growing Degree Days (thermal time) from sowing to 50% flowering and from sowing to maturity for Gadam and Seredo cultivars during the 2014 and 2015 crop growth seasons. The growing degree days (GDD) of sorghum from sowing to 50% flowering during April to August growing season (2014 and 2015) were 749°C and 868 °C days for the Gadam cultivar and 924°C and 1061 °C days for Seredo cultivar. During October to February growing season (2014 and 2015), the GDDs from sowing to 50% flowering were 1047°C and 949 °C days for Gadam and 1191°C and 1025 °C days for Seredo cultivar. On average, Seredo took extra days to flower (83) than Gadam (70) hence explaining the disparity in their respective GDDs.

Thermal units from sowing to maturity during April to August growing season (2014 and 2015) were 1404°C and 1366 °C days for the Gadam cultivar and 1492°C and 1422 °C days for Seredo cultivar. During October to February growing season (2014 and 2015), the GDDs from sowing to maturity were 1456°C and 1464 °C days for Gadam and 1548°C and 1554 °C days for Seredo cultivar. On average, Seredo took 6% more number of days to mature compared to Gadam (123 vs. 116 days) hence explaining the difference in GDDs. Generally Seredo took more thermal time as compared to Gadam probably due to the fact that it is a late maturity cultivar (KALRO, 2006).

Table 20: Duration of Gadam growth from sowing to maturity expressed in calendar days and growing degree days (°C days)

Stage	**Treatment**	**Calendar Days**				**GDD (°C days)**			
		Expt. 1	Expt. 2	Expt. 3	Expt. 4	Expt. 1	Expt. 2	Expt. 3	Expt. 4
50% flowering	N1P1	62	84	62	77	757	1048	877	955
	N2P1	61	84	61	79	744	1075	863	980
	N3P1	62	84	63	79	757	1075	890	980
	N4P1	60	84	61	79	732	1034	863	980
	N1P2	60	83	61	76	732	1048	877	943
	N2P2	61	82	60	75	732	1034	851	930
	N3P2	60	84	61	77	732	1034	863	955
	N4P2	62	84	62	76	757	1048	877	943
	N1P3	63	83	60	75	770	1034	863	930
	N2P3	61	83	60	75	744	1034	851	930
	N3P3	62	82	60	76	757	1034	863	943
	N4P3	63	83	61	74	770	1062	877	919
Maturity	N1P1	125	115	108	115	1399	1473	1380	1430
	N2P1	129	115	106	121	1427	1473	1360	1501
	N3P1	123	116	105	119	1381	1488	1350	1476
	N4P1	128	117	107	119	1427	1446	1368	1476
	N1P2	125	111	106	115	1389	1418	1360	1430
	N2P2	127	113	107	119	1408	1446	1368	1476
	N3P2	123	109	106	120	1381	1391	1360	1488
	N4P2	129	115	109	118	1435	1473	1390	1464
	N1P3	124	114	105	117	1381	1459	1350	1453
	N2P3	126	116	108	119	1408	1488	1368	1476
	N3P3	128	113	109	116	1417	1446	1390	1440
	N4P3	126	115	106	118	1399	1473	1350	1464

Base temperature =8°C (commonly used standard settings)

Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015, GDD=Growing Degree Days

Table 21: Duration of Seredo growth from sowing to maturity expressed in calendar days and growing degree days (°C days)

Stage	**Treatment**	**Calendar Days**				**GDD (°C days)**			
		Expt. 1	Expt. 2	Expt. 3	Expt. 4	Expt. 1	Expt. 2	Expt. 3	Expt. 4
50% flowering	N1P1	78	94	78	84	935	1193	1064	1041
	N2P1	78	93	77	84	935	1180	1054	1041
	N3P1	76	94	78	84	913	1193	1064	1041
	N4P1	78	94	77	84	935	1193	1054	1041
	N1P2	77	93	77	82	924	1180	1054	1017
	N2P2	77	94	76	82	924	1193	1043	1017
	N3P2	77	94	80	82	913	1206	1086	1004
	N4P2	78	93	76	81	935	1180	1043	1004
	N1P3	77	92	79	83	913	1180	1064	1030
	N2P3	76	94	76	82	913	1193	1043	1030
	N3P3	77	94	81	81	924	1193	1099	1004
	N4P3	77	95	78	83	924	1206	1064	1030
Maturity	N1P1	135	121	114	127	1499	1570	1438	1574
	N2P1	134	119	113	125	1488	1531	1428	1547
	N3P1	135	122	114	127	1499	1570	1438	1574
	N4P1	136	120	112	126	1509	1544	1408	1560
	N1P2	136	120	112	125	1509	1544	1417	1547
	N2P2	135	119	113	127	1488	1544	1428	1560
	N3P2	134	121	112	123	1477	1570	1417	1513
	N4P2	135	120	112	126	1467	1544	1417	1560
	N1P3	136	119	112	125	1499	1531	1417	1547
	N2P3	135	119	114	127	1499	1531	1438	1560
	N3P3	134	119	110	125	1488	1531	1399	1547
	N4P3	134	122	112	126	1477	1570	1417	1560

Base temperature =8°C (commonly used standard settings)

Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015, GDD=Growing Degree Days

4.3.3.1 Effect of Cultivar, Nitrogen and Phosphorus on Days to 50% Flowering

The effect of fertilizer treatments on days to 50% flowering of the sorghum crop is presented in Table 22. There was no significant difference amongst the treatments in the days to 50% flowering for both cultivars ($p< 0.01$ and $p<0.05$, Table 22) except for Experiment 4 (OND2015) for the Gadam cultivar whereby there was some significant difference between the control (N1P1) and some of the different treatments.

In experiments 1 and 3, days to 50% flowering in Gadam ranged from 60 to 63 days between different treatments. More days to 50% flowering were required in experiments 2 and 4 with days ranging from 82 to 84 and 74 to 79, respectively.

Seasonal effect portrayed a slower crop development by delaying days to 50 % flowering with an average of 22 days during the October to February growing season (83 days) compared to the April-August growing season (61 days) for Gadam cultivar (Expt. 2 vs. Expt.1). However, slightly less difference in the days to 50% flowering (17 days) was observed in Seredo cultivar (94 vs. 77). On the other hand, experiments 3 and 4 also depicted the same trend with slightly less difference between the two growing seasons (15 days and 5 days) for Gadam and Seredo cultivar, respectively. This is attributed to the excess rainfall received during the month of November which led to water logging; hence removal of oxygen on which roots of the two sorghum cultivars could depend on for respiration. However, the number of days to 50% flowering improved during the year 2015 for the OND season since the amount of rainfall received in the month of December was enough to meet the increased water requirements during the flowering stage compared to 2014 where the rainfall decreased.

Seredo cultivar took more days (86 and 82) to flower compared to the Gadam cultivar (72 and 69) during the year 2014 and 2015, respectively. Year effect on days to 50% flowering in sorghum was significant. The crop took more days to flower during 2014 as compared to 2015. This could be attributed to increased amounts of rainfall in 2015.

The effects of cultivar, N and P on days to 50 % flowering are presented in Table 23. Cultivar significantly affected days to 50 % flowering in all the four experiments ($p < 0.05$). The effect of N and P was not detected in the four experiments apart from experiment 4 where the effect of P was observed for the two cultivars. There were no observed significant ($P < 0.05$) interactive effects of N, P and cultivar in the four experiments (Table 23).

Table 22: Duration of Gadam and Seredo growth from sowing to 50% flowering expressed in calendar days after treatment with fertilizer

Treatment Combinations	N applied	P applied	Expt. 1		Expt. 2		Expt. 3		Expt. 4	
			G	**S**	**G**	**S**	**G**	**S**	**G**	**S**
			Calendar days							
N1P1	0	0	62	78	84	94	62	78	77bc	84
N1P2	0	50	60	77	83	93	61	77	76ab	82
N1P3	0	100	63	77	83	92	60	79	75ab	83
N2P1	50	0	61	78	84	93	61	77	79c	84
N2P2	50	50	61	77	82	94	60	76	75ab	82
N2P3	50	100	61	76	83	94	60	76	75ab	82
N3P1	75	0	62	76	84	94	63	78	79c	84
N3P2	75	50	60	77	84	94	61	80	77bc	82
N3P3	75	100	62	77	82	94	60	81	76ab	81
N4P1	100	0	60	78	84	94	61	77	79c	84
N4P2	100	50	62	78	84	93	62	76	76ab	81
N4P3	100	100	63	77	83	95	61	78	74a	83
Significance			NS	NS	NS	NS	NS	NS	**	NS

*Means with different unit weight letters in a column significantly differ from each other at p = 0.05. Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; G = Gadam; S = Seredo; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively*

Table 23: Effects of cultivar and fertilizer rates (N and P) on days to 50% flowering at Katumani

Effects	Expt. 1	Expt. 2	Expt. 3	Expt.4
	F- Probability			
Cultivar	*	*	*	*
N	NS	NS	NS	NS
P	NS	NS	NS	**
N*P	NS	NS	NS	NS
N*Cultivar	NS	NS	NS	NS
P*Cultivar	*	NS	NS	NS
N*P*Cultivar	NS	NS	NS	NS

*Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively.*

4.3.3.2 Effect of Cultivar, Nitrogen and Phosphorus on Days to Physiological Maturity

Significant difference ($p < 0.05$) among the different rates of fertilizer in the number of days to physiological maturity was not observed (Table 24) except for the Gadam cultivar in experiment 2. The yearly effect on days to maturity of sorghum was significant. The crop took lesser days to mature (116 days) during the year 2015, which was 6.9% lower as compared to the year 2014 (124 days). Sorghum took an average of one (1) extra day to mature during the April –August growing season (121days) compared to the October- February growing season (120 days). Seredo variety had the highest numbers of days to maturity in all the four experiments. This could be attributed to the fact that long season variety produces more tillers and that they have an extended grain filling period (Baumhardt *et al*., 2005).

Seasonal effect revealed faster crop development by decreasing days to physiological maturity by an average of 12 and 15 days during the October to February growing season (114 and 120 days) compared to the April-August growing season (126 and 135days) for Gadam and Seredo cultivars, respectively (Table 24). Delayed flowering which had occurred in the year 2014 for both cultivars contributed to decreased number of days to maturity. (Expt. 1 vs. Expt.2)

On the other hand, experiments 3 and 4 also depicted the opposite trend with increased days to maturity between the two growing seasons (12 days and 13 days) for Gadam and Seredo cultivar, respectively.

Highly significant ($p < 0.01$ and $p < 0.05$) cultivar effect on days to maturity was noted in experiments 1 and 2 (Table 25) with Seredo taking more days (128) to mature than Gadam (120). A significant interactive effect between N, P and cultivar was noted in experiment 4 ($P < 0.05$) (Table 25).

Table 24: Duration of Gadam and Seredo growth from sowing to maturity expressed in calendar days after treatment with fertilizer

Treatment Combinations	**N applied**	**P applied**	**Expt. 1**		**Expt. 2**		**Expt. 3**		**Expt. 4**	
			G	**S**	**G**	**S**	**G**	**S**	**G**	**S**
			Calendar days							
N1P1	0	0	125	135	115e	121	108	114	115	127
N1P2	0	50	125	136	111b	120	106	112	115	125
N1P3	0	100	124	136	114d	119	105	112	117	125
N2P1	50	0	129	134	115e	119	106	113	121	125
N2P2	50	50	127	135	113c	119	107	113	119	127
N2P3	50	100	126	135	116f	119	108	114	119	127
N3P1	75	0	123	135	116f	122	105	114	119	127
N3P2	75	50	123	134	109a	121	106	112	120	123
N3P3	75	100	128	134	113c	119	109	110	116	125
N4P1	100	0	128	136	117g	120	107	112	119	126
N4P2	100	50	129	135	115e	120	109	112	118	126
N4P3	100	100	126	134	115e	122	106	112	118	126
Significance			NS	NS	**	NS	NS	NS	NS	NS

*Means with different unit weight letters in a column significantly differ from each other at p = 0.05. Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; G = Gadam; S = Seredo; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively*

Table 25: Effects of cultivar and fertilizer rates (N and P) on days to maturity at Katumani

Effects	**Expt. 1**	**Expt. 2**	**Expt. 3**	**Expt.4**
	F- Probability			
Cultivar	**	*	NS	NS
N	NS	**	NS	NS
P	NS	**	NS	NS
N*P	NS	**	NS	NS
N*Cultivar	NS	**	NS	NS
P*Cultivar	NS	**	NS	NS
N*P*Cultivar	NS	NS	NS	*

*Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively.*

4.3.3.3 Effect of Cultivar, Nitrogen and Phosphorus on Above Ground Total Biomass Accumulation

The effects of different treatments on biomass accumulation at harvest in all the four experiments are presented in (Table 26). Biomass responded insignificantly to the different rates of fertilizer application rates in both cultivars except for experiment 2. Biomass accumulation of sorghum at harvest was 74.9% higher during the October to February growing season (5585kgha^{-1}) compared to the April-August growing season (3193kgha^{-1}) for the two years. This was due to comparably higher rainfall amounts received during the OND season. The ANOVA (Table 27) showed significant cultivar effect in experiments 2 and 4. Seredo had significantly higher biomass than Gadam with percentage difference of 84.1% and 39.9% in Experiments 2 and 4, respectively. Generally, Seredo produced a higher average biomass (27.3 %) than Gadam in all the four experiments. This could be due to longer grain filling period, increased vegetative growth and longer periods of photosynthesis which was associated with Seredo cultivar and also due to enhance fertilizer application.

Significant effects were also noted with N and P application rates for both cultivars in experiment 2. This suggests that both cultivars were responsive to both N and P rates and that an increase in N and P application resulted to an increase in the accumulation of biomass. These results are in conformity with Kayuki *et al*., (2012) who also reported increase in sorghum biomass with application of nitrogen.

N application significantly increased biomass accumulation in Seredo by 12.3 and 12.2% with application of 50Nkgha^{-1} over the control for experiments 1 and 4, respectively over the control for experiments 1 and 4, respectively (Table 26). However, the accumulation of biomass started decreasing at higher levels of N (75 and 100kgha^{-1}). Thus, at higher levels of N, other factors (environmental effects and other soil nutrients or both) could have been limiting to biomass accumulation (Table 26). Significant differences in biomass accumulation at harvest were observed between 0, 50 and 100 Pkg ha^{-1} at similar levels of N within experiment 2. Experiment 1 showed the lowest biomass accumulation ranging from 2072 kgha^{-1} in N1P1 to 3326kgha^{-1} in N3P2. Hence, biomass accumulation was categorized (Table 26) in the increasing order of Expt. 1 < Expt. 3 < Expt. 2 < Expt. 4.

Comparable observations were made for the Gadam cultivar biomass accumulation at harvest. Experiment 4, had a large amount biomass accumulation of 7660kgha^{-1} in N4P2 while the lowest of 1448kgha^{-1} in N1P3 was recorded in experiment 1 (Table 26).

Significant yearly effect on biomass accumulation of sorghum was observed. The crop accumulated more biomass during 2015 (5614kgha^{-1}) as compared to 2014 (3164kgha^{-1}). The attribution is the high amounts of rainfall that was recorded in the year 2015. High amounts of rainfall and favorable temperature lead to excessive vegetative growth, thus higher biomass accumulation.

Table 26: Biomass accumulation of Gadam and Seredo cultivars at harvest at Katumani

Treatment Combinations	**N applied**	**P applied**	**Expt. 1**		**Expt. 2**		**Expt. 3**		**Expt. 4**	
			G	**S**	**G**	**S**	**G**	**S**	**G**	**S**
			Calendar days							
N1P1	0	0	2773	2072	2274e	4183f	3014	4107	5929	8448
N1P2	0	50	4151	3228	2400g	3543a	2596	5121	6511	8084
N1P3	0	100	1448	2859	3531k	3917b	3697	3766	6539	8659
N2P1	50	0	2476	2326	3441j	4424h	2959	3921	5429	9486
N2P2	50	50	3361	2631	2426h	4382g	3119	3298	6020	8694
N2P3	50	100	3465	2994	3367i	4104e	3522	4571	6955	8392
N3P1	75	0	4126	2775	1287a	4055d	2391	4089	6230	9038
N3P2	75	50	1956	3326	1522c	4002c	2992	4026	6002	8102
N3P3	75	100	2591	2694	1438b	6027l	2771	3523	6622	11002
N4P1	100	0	3107	2600	1711d	5575k	3043	4270	5598	7553
N4P2	100	50	2006	2455	2397f	5276i	3532	4579	7660	10121
N4P3	100	100	2608	3291	3963l	5298j	3473	3565	7000	9440
Significance			NS	NS	**	**	NS	NS	NS	NS

*Means with different unit weight letters in a column significantly differ from each other at p = 0.05. Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; G = Gadam; S = Seredo; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively*

Table 27: Effects of cultivar and fertilizer rates (N and P) on biomass accumulation at Katumani

Effects	Expt. 1	Expt. 2	Expt. 3	Expt.4
	F- Probability			
Cultivar	NS	**	NS	**
N	NS	**	NS	NS
P	NS	**	NS	NS
N*P	NS	**	NS	NS
N*Cultivar	NS	**	NS	NS
P*Cultivar	NS	**	NS	NS
N*P*Cultivar	NS	**	NS	NS

*Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively.*

4.4.3.4 Effect of Cultivar, Nitrogen and Phosphorus on Grain Yield

Sorghum grain yields at harvest for both cultivars are presented in (Table 28). The ANOVA showed a significant response of Seredo cultivar among the different rates of fertilizer ($p < 0.05$ and $p < 0.01$, Table 29) in experiment 2. Assessment of rainfall and yields in 2014 and 2015 shows the importance of rainfall distribution during the growing period and in particular during critical growth stages. There was approximately 1261kgha^{-1} sorghum grain yield in 2014 compared to 2593kgha^{-1}in 2015 (Table 28). This was due to water stress during the vegetative and reproductive phase that occurred in 2014.

The seasonal effect on grain yield was also evident with a 69.7 % higher grain yield in October-February growing season (2425kgha^{-1}) than in the April-August growing season (1429kgha^{-1}). This was most likely due to water stress that occurred during the April-August growing season. On average sorghum cultivar effect on grain yield was insignificant (Table 29), with Seredo producing 17.1 % more grain yield than Gadam. The Seredo cultivar produced 1.7 %, 22.6 % and 32.8% more grain than Gadam in experiments 1, 2 and 4, respectively. The late cultivar attained higher yield because of the longer grain filling period and the increased vegetative growth.

In general, N insignificantly increased grain yield of Seredo cultivar in experiments 1, 2 and 4 at 0, 50 and 75kgha^{-1} levels of N with no P application. The sole application of P upto 50kgha^{-1} also increased grain yield for Seredo (experiment 1 and 3). The findings of this study agree with Stewart, 2003; Ashiano *et al*., 2005; Alemu and Bayo, 2005; Kayuki *et al*., 2012 who reported that sorghum grain yield increased with increase in nitrogen rates. Seredo grain yield in experiments 1, 2 and 4 responded positively to application of nitrogen with yields ranging from 952kgha^{-1}, 1203kgha^{-1} and 4332kgha^{-1} in N1P1 (control) to yield maximum of 1337kgha^{-1}, 1397kgha^{-1} and 5088kgha^{-1} in N3P1, representing an increase of 40.4%, 16.1% and 17.5%, respectively.

The response of Gadam cultivar to N, P and their interactive effects was insignificant in the majority of experiments. In general, grain yield was categorized (Table 28) in the decreasing order of Expt. 4 > Expt. 3 > Expt. 2 > Expt. 1 for both cultivars.

Table 28: Effect of nitrogen and phosphorus fertilizer on Gadam and Seredo cultivars grain yield at Katumani

Treatment Combinations	**N applied**	**P applied**	**Expt. 1**		**Expt. 2**		**Expt. 3**		**Expt. 4**	
			G	**S**	**G**	**S**	**G**	**S**	**G**	**S**
			Calendar days							
N1P1	0	0	1047	952	960	1203d	1637	1569	3225	4332
N1P2	0	50	1964	1613	1117	1011a	1126	1818	3119	3506
N1P3	0	100	546	1412	1001	1146c	1906	1411	3284	3566
N2P1	50	0	1046	1190	1530	1275f	1576	1703	2820	4391
N2P2	50	50	1533	1291	1276	1307g	1583	1244	2783	4079
N2P3	50	100	1615	1323	1488	1344h	1894	1805	3007	4289
N3P1	75	0	1984	1337	599	1258e	1651	1397	3139	5088
N3P2	75	50	939	1582	739	1056b	1540	1318	2790	3396
N3P3	75	100	1264	1284	729	1798l	1230	1125	3540	5210
N4P1	100	0	1370	1184	1030	1598j	1593	1532	2794	3625
N4P2	100	50	1005	1177	1122	1661k	1523	1699	3524	4104
N4P3	100	100	1220	1458	1522	1416i	1863	1531	3435	4176
Significance			NS	NS	NS	**	NS	NS	NS	NS

*Means with different unit weight letters in a column significantly differ from each other at p = 0.05. Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; G = Gadam; S = Seredo; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively*

Table 29: Effects of cultivar and fertilizer rates (N and P) on sorghum grain yield at Katumani

Effects	**Expt. 1**	**Expt. 2**	**Expt. 3**	**Expt.4**
	F- Probability			
Cultivar	NS	NS	NS	NS
N	NS	*	NS	NS
P	NS	NS	NS	NS
N*P	NS	NS	NS	*
N*Cultivar	NS	NS	NS	NS
P*Cultivar	NS	NS	NS	NS
N*P*Cultivar	NS	NS	NS	NS

*Expt. 1 = April-August growing season 2014; Expt. 2 = October-February growing season 2014; Expt. 3 = April-August growing season 2015; Expt. 4 = October-February growing season 2015; NS = Non-significant; *, ** = Significant at 95% and 99%, respectively.*

4.4 APSIM Model Calibration and Evaluation

The genetic coefficients of sorghum crop were obtained by repeated adjustment of parameters of the APSIM model until a close relationship between the observed and simulated sorghum parameters were obtained. Genetic coefficients of the two sorghum cultivars used by APSIM are as shown in Table 30. Comparison between observed and simulated phenological dates, biomass and grain yield for sorghum is shown in Table 31and 32.

Table 30: Genetic coefficients used for modeling the two sorghum cultivars in APSIM

Parameter		Source	Units	Gadam	Seredo
Thermal time accumulation	End of juvenile phase to panicle initiation	C	°C day	100	125
	Flag stage to flowering	C	°C day	100	100
	Flowering to start of grain filling	C	°C day	30	80
	Flowering to maturity	C	°C day	761	695
	Maturity to seed ripening	L	°C day	1	1
Photoperiod	Day length photoperiod to inhibit flowering	D	Hours	12.3	11.5
	Day length photoperiod for insensitivity	D	Hours	14.6	13.5
	Base temperature	L	°C day	8	8

C: calibrated; D: Default; L: literature

4.4.1 Days to 50% Flowering

The disparity in days to 50% flowering between the two cultivars at particular N rates suggested that the effects of Nitrogen application rates on sorghum phenology varied among cultivars. This was also replicated in the model simulations (Table 31 and 32).

Generally the model over estimated the days to 50% flowering compared to the observed days for most of the treatments. The RMSE values for all the treatments between the observed and the simulated days to 50% flowering for the MAM growing season was 1.2 and 1.6 days for the Gadam and Seredo cultivars, respectively (Table 31). On the other hand, the RMSE values for OND growing season were 1.0 and 1.3 days for the Gadam and Seredo cultivars, respectively (Table 32). Thus APSIM simulated days to 50% flowering of both cultivars reasonably well for both seasons, where the simulated values were in agreement with the observed values. Lesser values of RMSE imply that the model is in a better position in explaining most of the variations.

Data indicate that the simulated days to 50% flowering values for Gadam cultivar reasonably matched observed values, owing to the modified index of agreement (d_m) of 0.5 and above for both the long and short growing seasons. However, the variation in Seredo simulations represent some error level as indicated by very low values of modified index of agreement (d_m) in both the long and short growing seasons. The d_m values close to 1 are considered as better simulations (Table 31 and 32).

There was a good correlation between observed and simulated days to 50% flowering for both cultivars during the long and short rainfall seasons with r^2 values ranging between 45 % and 99% (Table 31 and 32).

4.4.2 Days to Physiological Maturity

Similarly, at a particular Nitrogen rates, the differences in days to physiological maturity was also noted in the observed and simulated results among the cultivars. Days to physiological maturity was generally over estimated by the model especially during the MAM growing season for both cultivars.

The values of RMSE between observed and simulated days to physiological maturity for the Gadam cultivar were 2.4 and 1.0, for the MAM and OND growing seasons, respectively. For

Seredo the values were 2.9 and 1.2 days, during the MAM and OND growing seasons, respectively (Table 31 and 32). The RMSE values were relatively low during the OND season and also relatively low for the Gadam cultivar. This indicates that the model performed well during the OND season and also in replicating the observed days to physiological maturity for the Gadam cultivar.

The values for the modified index of agreement across the cultivars during the MAM and OND growing season ranged between 0.4 and 0.8. Hence the model was deemed satisfactory (Table 31 and 32).

APSIM model accounted for relatively higher percentage of the total variation of the observed days to physiological maturity for the Gadam cultivar during both the long and short rainfall season with r^2 values of 76.2 and 85.9 % (Table 31 and 32).

4.4.3 Total Above Ground Biomass at Harvest

Sorghum biomass at harvest simulated by APSIM model reasonably matched observed values during the MAM and OND growing seasons of 2015.

The RMSE values for MAM growing season were 347.6 $kgha^{-1}$ and 360.7 $kgha^{-1}$ and for OND growing season were 369.6 $kgha^{-1}$ and 427.2 $kgha^{-1}$ for Gadam and Seredo cultivars, respectively (Table 31 and 32).

Higher values of modified index of agreement showed more precise simulation of total biomass. The values were greater than or equal to 0.5 (Table 31 and 32). The comparison between the observed and simulated total biomass showed a good agreement between the two, with r^2 values of 87.9 and 69.0 % for Gadam and for Seredo 48.1and 78.4% during the MAM and OND growing seasons, respectively (Table 31 and 32).

The values of the modified index of agreement and r^2 corroborate with the findings of Wilmott *et al*. (1985) that modified index of agreement and r^2 values between observed and simulated data close to 1 show a good performance of the model.

Simulated total biomass was consistently over estimated by the model compared to the observed biomass. This could be attributed to the fact that during field trials, a proportion of leaves have senesced and fallen off the plant by the time the plant reaches maturity. Often these fallen leaves are not collected during plant sampling. The model does not simulate the detachment of the senesced leaves, and thus the estimated values could often be higher than the observed.

Table 31: Statistical indicators of APSIM model performance during the long rains

Parameter/Cultivars	**Gadam**			**Seredo**		
	RMSE	**d**	**R^2 (%)**	**RMSE**	**d**	**R^2 (%)**
Days to 50% flowering	1.2	0.5	45.0	1.6	0.4	50.0
Days to Maturity	2.4	0.6	76.2	2.9	0.4	43.3
Biomass	347.6	0.5	87.9	360.7	0.5	48.1
Yield	52.3	0.6	56.0	227.7	0.5	81.0

RMSE: root mean square error, d_m: modified index of agreement and R^2: coefficient of determination

Table 32: Statistical indicators of APSIM model performance during the short rains

Parameter/Cultivars	**Gadam**			**Seredo**		
	RMSE	**d**	**R^2 (%)**	**RMSE**	**d**	**R^2 (%)**
Days to 50% flowering	1.0	0.5	99.0	1.3	0.4	53.3
Days to Maturity	1.0	0.8	85.9	1.2	0.4	47.3
Biomass	369.6	0.5	69.0	427.2	0.6	78.4
Yield	155.9	0.6	96.0	196.3	0.8	87.6

RMSE: root mean square error, d_m: modified index of agreement and R^2: coefficient of determination

4.4.4 Grain yield

Yield is the most important component as it is the economic and food part of the crop. In general, the model simulated sorghum grain yield fairly well in all the seasons for both cultivars, with RMSE values ranging from 52.3 kgha^{-1} to 227.7kgha^{-1} and modified index of agreement (d_m) between 0.5 to 0.8 across the cultivars and seasons.

The overall coefficients of determination (r^2) values for MAM growing season were 56.0 and 81.0 % and for OND growing season were 96 and 87.6% for Gadam and Seredo cultivars, respectively (Table 31 and 32).

The grain yield at maturity was generally over estimated by the model. Sorghum grain yields were better simulated during MAM season for the Gadam cultivar and OND season for Seredo cultivar (Table 31 and 32).

A simulation is always an estimate but what is important is to what degree it is replicating the observed. This is because it is a simplification and approximation of reality and thus it cannot take into account of everything. On the other hand, there can be sampling errors which can lead to differences between observed and predicted values, so one has to check the 'sensibility' of the observed data, besides the 'sensibility' of the simulated results.

Results in this study point out that APSIM has a propensity to slightly over estimate the phenology, growth and grain yield. However, the error in all the parameters was below 15%, which is judged acceptable (Ritchie *et al.*, 1998; Brassard, 2003). Therefore these slight deviations in APSIM will not influence the final trends obtained as much as climate change impact and adaptation studies are concerned. The results obtained here showed that genetic coefficients estimated for each cultivar were robust and once a model is calibrated for a cultivar, it can with high degree of accuracy simulate growth and yield. The calibrated model was used to simulate sorghum growth and development under three scenarios of climate change (near-term, mid-century and end-century).

4.5 Assessment of the Performance of CORDEX in Simulating Climate Parameters

Observational data from Katumani meteorological station was used since it was the only station with data on the three climate parameters (rainfall, temperature and solar radiation). An initial assessment using the seasonal (MAM and OND) and annual rainfall totals showed that there was significant linear association at 99% confidence level between rainfall at Katumani and the other two rainfall stations.

Comparisons of daily GCM outputs and observed data during the MAM and OND seasons are presented in Table 33. The results for each metric are discussed in the subsequent sub sections and finally ranking was done based on individual metric results. Thereafter an overall ranking based on the overall summation of individual ranks sum of the three metrics was provided.

4.5.1 GCM outputs and Observed Data

Prior to assessing the performance of the GCMs in simulating observed data, it is essential to explain the characteristics of the data (observed and model).

Observed, NorESM-M, MPI-ESM-LR, MIROC5 and Ensemble depicted symmetry in seasonal rainfall distribution for both seasons (Figures 12a and 12b). CanESM2, CNRM and EC-Earth rainfall data was skewed to the right suggesting that the same models overestimated rainfall. Overestimation of the observed rainfall is more noticeable in the MAM season (Figure 12a) than the OND season (Figure 12b). The less bias in the GCMs predicting rainfall during the OND season is attributed to the fact that the OND seasonal rainfall is mostly influenced by large scale systems (Mutai and Ward, 2000).

For seasonal temperature (Figures 13a, 13b, 13c and 13d); NorESM1, MPI and Ensemble seem to replicate both the observed maximum and minimum temperature reasonably well as compared to the other GCMs. During both seasons the median for maximum temperature is at all times equal or greater than the GCM outputs (Figure 13a and 13b). This simply indicates that GCMs tend to predict higher values of maximum temperatures than the observation. However, for the minimum temperature the median is at all times equal or lower than the GCM outputs (Figure 13c and 13d) indicating that GCMs tend to predict lower values of minimum temperatures as compared to the observed data. There is less bias in the GCMs when simulating temperature than when simulating rainfall at any time scales. This is largely due to the more steady nature of temperature making it easily predicted.

Lastly the seasonal solar radiation (Figure 12c and 12d), during the MAM season, NorESM1, GFDL and CNRM over estimated the observed solar radiation since their medians, 1st and 3rd quartiles were higher than the observed. MPI and ensemble showed similar observations to the observed data (Figure 12c). During the OND season (Figure 12d), all the GCMS except CNRM and ensemble underestimated the observed solar radiation data because their medians, 1st and 3rd quartiles were lower than the observed data.

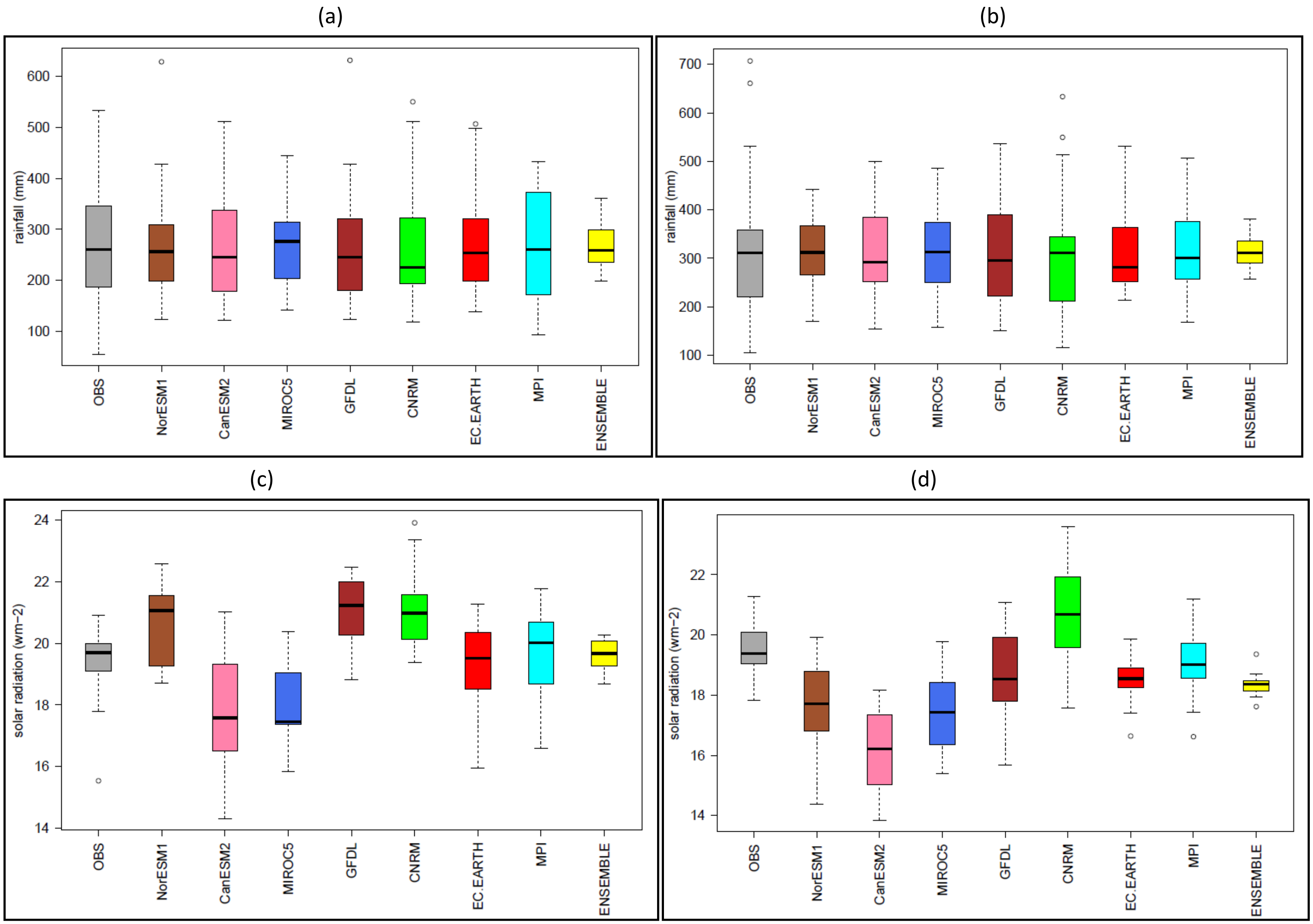

Figure 12: Box plots illustrating the distribution of rainfall and solar radiation in observations and models. Left and right panels represent March-May and October- December season, respectively.

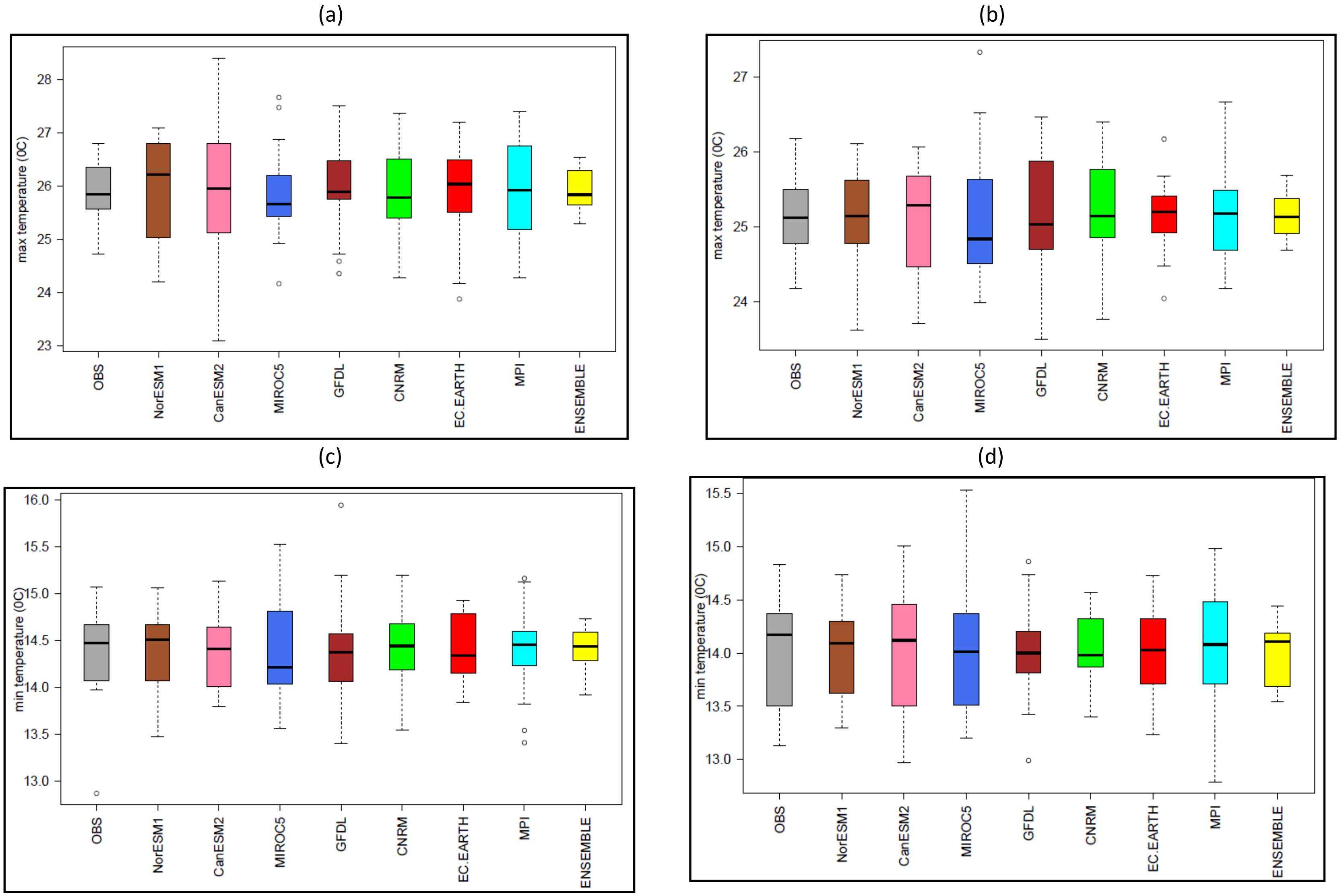

Figure 13: Box plots illustrating the distribution of maximum and minimum temperature observations and models. Left and right panels represent March-May and October- December season, respectively.

4.5.2 Root Mean Square Error

Results of the RMSE for each GCM and observed data are displayed in Table 33, lower values of RMSE indicates the variations in the observed data can be best explained by the model. It can be observed from Table 33 that the ensemble performs better in simulating the three climate variables since the values of RMSE are relatively lower compared to the rest of the GCMs. This is attributed to ensemble accommodating information from each individual model (Pincus *et al.*, 2008), thus enabling them to be superior to individual models.

In general both the GCMs and the ensemble showed weaker values of RMSE in simulating rainfall as compared to temperature and solar radiation. This indicates that their skill in simulating temperature and solar radiation are higher than the skill for simulating rainfall. The weaker values of RMSE for rainfall are an indication of low agreement between the models and observed data.

EC-EARTH, MIROC5, MPI and CNRM-CM5 are examples of GCMs that performed poorly in replicating the observed fields within the study area.

4.5.3 Modified Index of Agreement

Modified index of agreement (d_m) was performed on observed and GCM data at daily timescale for the two seasons. Modified index of agreement statistics were then compared to provide model ranking, for the three climate variables (rainfall, temperature and solar radiation). Results of Modified index of agreement are presented in Table 33.

The modified index of agreement values ranged from 0.19 to 0.54 across the climate variables and seasons. The values close to one (1) are considered as better simulations and according to the values obtained the ensemble displayed relatively higher values of d_m except for rainfall. This indicates a relatively better fit of the model and that the ensemble performed relatively well in simulating both temperature and solar radiation.

Table 33: Performance statistics comparing CORDEX GCM models root mean square error and modified index of agreement for daily rainfall, maximum and minimum temperature, and solar radiation with concurrent observed data during the March to May and October to December Seasons

March to May								
	Rainfall		**Maximum Temperature**		**Minimum Temperature**		**Solar Radiation**	
GCM name	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$
CanESM2	1.365	0.423	1.073	0.480	1.338	0.323	1.135	0.305
CNRM-CM5	1.408	0.405	1.147	0.453	1.388	0.301	1.163	0.299
EC-EARTH	1.391	0.399	1.105	0.459	1.473	0.266	1.157	0.311
MIROC5	1.385	0.401	1.234	0.385	1.347	0.321	1.305	0.262
MPI-ESM-LR	1.390	0.407	1.084	0.470	1.421	0.293	1.126	0.321
NorESM1-M	1.391	0.409	1.209	0.392	1.367	0.308	1.213	0.297
GFDL-ESM2M	1.376	0.425	1.003	0.508	1.398	0.302	1.104	0.319
Ensemble	1.352	0.310	0.975	0.541	1.362	0.319	0.978	0.482
October to December								
	Rainfall		**Maximum Temperature**		**Minimum Temperature**		**Solar Radiation**	
GCM name	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$	**RMSE**	$\mathbf{d_m}$
CanESM2	1.349	0.421	1.336	0.333	1.336	0.317	1.470	0.202
CNRM-CM5	1.394	0.389	1.374	0.325	1.434	0.275	1.474	0.209
EC-EARTH	1.417	0.383	1.356	0.329	1.400	0.293	1.489	0.196
MIROC5	1.393	0.407	1.298	0.373	1.399	0.287	1.394	0.242
MPI-ESM-LR	1.384	0.393	1.414	0.300	1.423	0.280	1.513	0.189
NorESM1-M	1.390	0.405	1.256	0.393	1.368	0.302	1.349	0.246
GFDL-ESM2M	1.377	0.406	1.349	0.340	1.367	0.306	1.427	0.227
Ensemble	1.352	0.294	1.262	0.381	1.375	0.298	1.445	0.259

RMSE, r^2, and d_m denote the Root mean square error, coefficient of determination and modified index of agreement, respectively.

4.5.4 Overall Performance

Performance of the GCMs were evaluated using two (2) metrics for rainfall, maximum and minimum temperature and solar radiation, for the two seasons totaling to 16 metrics on daily and every model was given a score of 1-8 in each of the metrics. Overall rank sum and the overall ranking for rainfall, maximum and minimum temperature and solar radiation, was provided using all the 16 metrics. The metrics obtained for each model on daily time scales is presented in Table 35. From Table 34 it can be deduced, based on overall performance, that the ensemble, CanESM2, GFDL-ESM2M, NorESM1-M, MIROC5, MPI-ESM-LR, EC-EARTH and CNRM-CM5 (in order of decreasing ranking) were able to simulate observed climate variables in the desired period for the study region.

Table 34: CORDEX GCMs ranking (rank 1=best) based on root mean square error and modified index of agreement values from comparison of observed data and 7 models plus the ensemble

GCM Name	**Root mean square error (rank)**									**Modified index of agreement (rank)**										
	MAM				**OND**				**Rank sum**	MAM				**OND**				**Rank sum**	**Overall rank sum**	**Overall rank**
	Rain	Max	Min	Slr	Rain	Max	Min	Slr		Rain	Max	Min	Slr	Rain	Max	Min	Slr			
CanESM2	2	3	1	4	1	4	1	5	**21**	2	3	1	5	1	5	1	6	**24**	**45**	***2***
CNRM-CM5	8	6	5	6	7	7	8	6	**53**	5	6	6	6	6	7	8	5	**49**	**102**	***8***
EC-EARTH	7	5	8	5	8	6	6	7	**52**	7	5	8	4	7	6	5	7	**49**	**101**	***7***
MIROC5	4	8	2	8	6	3	5	2	**38**	6	8	2	8	2	3	6	3	**38**	**76**	***5***
MPI-ESM-LR	5	4	7	3	4	8	7	8	**46**	4	4	7	2	5	8	7	8	**45**	**91**	***6***
NorESM1-M	6	7	4	7	5	2	4	1	**36**	3	7	4	7	4	1	3	2	**31**	**67**	***4***
GFDL-ESM2M	3	2	6	2	3	5	2	3	**26**	1	2	5	3	3	4	2	4	**24**	**50**	***3***
Ensemble	1	1	3	1	1	1	3	4	**15**	8	1	3	1	8	2	4	1	**28**	**43**	***1***

Rain, max, min and slr represents rainfall, maximum temperature, minimum temperature and solar radiation, respectively

4.6 Impact of Climate Change on Sorghum Productivity

In this section results presented are comparisons of simulated phenological dates, total biomass and sorghum yield under current climate (1976 -2005) and three scenarios climate change (2010-2039, 2040-2069 and 2070-2099) using RCP 4.5 and RCP 8.5 for Machakos County in Kenya. Sorghum growth and development is compared for a short season cultivar (Gadam) and for a long season cultivar (Seredo). Prior to studying climate change impacts on sorghum productivity, the delta-based CORDEX models projections were obtained and discussed. Only the CORDEX GCMs that performed relatively well in simulating the climate variables were used for impact study.

4.6.1 Climate Change Projections

This section presents the results of the delta-based CORDEX models projections in the three future time slices (2010-2039, 2040-2069 and 2070-2099) in relation to the baseline period (1976-2005).

4.6.1.1 Temperature Change across the CORDEX Models

The CORDEX models consistently projected increased temperatures (warmer future) in all the three future time slices under the two RCPs with a mean temperature increase ranging from +0.8°C to 3.8°C (Table 35). The results agree with the findings by IPCC, (2013) and Msongaleli *et al.*, (2015) who predicted increases in temperature in most climate change scenarios. NorESMI-M model projected both the lowest and the highest increase in the mean temperature over the entire period under the two RCPs.

Projected changes in both minimum and maximum temperature are displayed in Table 35. NorESMI-M model showed the lowest (0.6°C) projected increase in maximum temperature, under the RCP4.5 and RCP 8.5 for the period 2010-2039, whereas GFDL-ESM2M model and ensemble showed the highest (3.2°C) projected increase in maximum temperature, under the RCP 8.5 for the period 2070-2099.

The NorESMI-M model and ensemble projected the lowest increase in minimum temperature in the 2010-2039 future period under RCP4.5, while CanESM2 projected the highest (4.8°C) increase in minimum temperature for the period 2070-2099 under RCP8.5.

The projected maximum and minimum temperature changes depicted strong uniformity with an increasing trend across all the GCMs within the two RCPs. Similar findings were reported by Msongaleli *et al*., (2015) in central Tanzania.

4.6.1.2 Rainfall Change across the CORDEX Models

As is regularly observed in most of climate change studies, there is a tendency in rainfall projections being more uncertain and diverse than the projections of temperature (Solomon *et al*., 2007; Arndt *et al.,* 2010). In the current study rainfall results revealed uncertainty across the CORDEX models.

All the GCMs considered show increase in precipitation (wetter future) in the three future periods under both RCP4.5 and RCP8.5 as compared to the current climate. Projected mean rainfall changes across all the GCMs under the two RCPs were 8.2%, though varying considerably across GCMs. The mean projected rainfall change under the RCP 4.5 and RCP 8.5 was 6.6% and 9.7%, respectively. This indicates slightly wetter conditions in the future under the RCP8.5 compared to RCP4.5.

The GFDL-ESM2M model projects the lowest increase (1.2%) in rainfall in the 2010-2039 future period under RCP8.5, while the CanESM2 projected the highest (26.3%) increase in rainfall for the period 2070-2099 under RCP8.5 (Table 35).

4.6.1.3 Solar Radiation Change across the CORDEX Models

The GFDL-ESM2M model projects the highest (-0.1%) increase in solar radiation in the 2010-2039 future period under RCP8.5, whereas, CanESM2 and NorESMI-M models showed the lowest (-2.5%) projected increase in solar radiation, under the RCP 4.5 and 8.5, respectively (Table 35).

Table 35: Mean change in projected climate between baseline (1976-2005) and the three future time slices (2010-2039, 2040-2069 and 2070-2099) periods for RCP 4.5 and RCP 8.5

Name of Model	**Parameter**	**RCP 4.5**			**RCP8.5**		
		2010-2039	**2040-2069**	**2070-2099**	**2010-2039**	**2040-2069**	**2070-2099**
GFDL-ESM2M	Maximum Temperature (°C)	0.7	1.3	1.7	0.9	2.0	3.2
	Minimum Temperature (°C)	1.1	1.7	2.1	1.2	2.4	3.8
	Mean Temperature (°C)	0.9	1.5	1.9	1.1	2.2	3.4
	Rainfall (%)	1.5	1.9	6.6	1.2	3.9	15.6
	Solar Radiation (%)	-0.6	-0.7	-0.9	-0.1	-0.9	-1.6
CanESM2	Maximum Temperature (°C)	1.0	1.8	2.4	1.0	1.1	2.4
	Minimum Temperature (°C)	1.2	2.2	2.7	1.5	3.0	4.8
	Mean Temperature (°C)	1.1	2.0	2.6	1.3	2.1	3.1
	Rainfall (%)	6.8	9.5	14.7	5.4	11.3	26.3
	Solar Radiation (%)	-1.2	-2.5	-1.1	-2.3	-1.6	-1.9
NorESMI-M	Maximum Temperature (°C)	0.6	1.2	1.3	0.6	1.7	2.9
	Minimum Temperature (°C)	1.0	1.6	1.9	1.1	2.2	3.6
	Mean Temperature (°C)	0.8	1.4	1.6	0.9	1.9	3.8
	Rainfall (%)	2.6	1.5	6.9	4.3	3.3	9.9
	Solar Radiation (%)	-1.4	-1.2	-2.3	-1.6	-1.9	-2.5
Ensemble	Maximum Temperature (°C)	0.8	1.4	1.8	0.8	1.8	3.2
	Minimum Temperature (°C)	1.0	1.8	2.2	1.2	2.4	4.0
	Mean Temperature (°C)	0.9	1.6	2.0	1.0	2.1	3.6
	Rainfall (%)	5.0	9.7	12.3	6.2	8.9	20.5
	Solar Radiation (%)	-0.8	-1.1	-1.3	-0.8	-1.1	-1.6

4.6.2 Comparison on Days to 50% Flowering Under Both Current and Future Climate

All GCMs showed that the application of nitrogen fertilizer at 0N and 50N had little or no effect on the days taken by the two sorghum cultivars to attain 50% flowering (Figure 14).

The mean number of days taken by the short season cultivar, Gadam, to reach 50% flowering was 73 and 70 for the MAM and OND growing season, respectively under current climate. Nevertheless, under RCP4.5 and 8.5, the number of days was reduced by 11, 16 and 19 and 11, 19 and 26 for the near term, mid century and end century, respectively during the MAM season. During the OND season, the number of days for the Gadam to reach 50% flowering reduced by 6, 11 and 13 for the near term, mid century and end century, respectively, under RCP4.5 and 7, 14 and 21, respectively under RCP8.5 (Table 36)

Under current climate the Seredo cultivar took 85 days and 78 days to reach 50% flowering (Figure 14) during the MAM and OND season, respectively. However, this was reduced to 72, 66 and 62 days under RCP4.5 for the near term, mid century and end century, respectively during the MAM season, under RCP8.5 the days reduced to 73, 62 and 52 days. During the OND season, the days taken by Seredo to reach 50% flowering reduced to 69, 66 and 63 for the near term, mid century and end century, respectively, under RCP4.5. In addition, the days reduced to 70, 63 and 55 days under RCP8.5 (Table 36). Hence, under RCP4.5 and RCP8.5 in the near term (2020's) the number of days to reach 50% flowering for the long season cultivar approximates that of the short season cultivar, under baseline climate.

It is also evident from the study, that the short season cultivar, Gadam, took less days to reach 50% flowering compared to the long season cultivar, Seredo, under both the current climate and changed climate (Figure 14).

Both cultivars took considerably more days to reach 50% flowering under current climate than under climate change (Figure 14). This outcome is attributed to increase in temperature and rainfall creating favorable conditions for sorghum growth and development. Increased temperature accelerates growth and development of sorghum and thus reducing the length from sowing to 50% flowering. Increased temperature leads to quick accumulation of heat units from sowing to 50% flowering; hence the sorghum plant flowered earlier (Baviskar *et al*., 2017).

Projected mean changes on days to 50% flowering showed a consistent decline for both sorghum varieties during both the long and short growing season with the application of different rates of fertilizer (Table 36). The decline was relatively higher during the MAM season as compared to the OND season, implying that the number of days to 50% flowering will be less during the MAM growing season for the two varieties. The results also indicated that towards the end century (2080’s) under both RCPs there will be great decline in the number of days to 50% flowering when compared to the current climate (baseline).

The decrease in number of days to 50% flowering, under climate change revealed in this study corroborate results obtained by Wang *et al*., (2011), who reported that flowering dates reduced by 2, 3 and 4 days by 2020, 2050 and 2070, respectively.

Generally the days taken by both cultivars to reach 50% flowering, show slightly more variability under current climate than under projected climate during the MAM season (Figure 15a and15c). However, during the OND season (Figure 15b, 15d); the variability under current climate is slightly lower compared to that under climate change. The models used were able to capture the variability of the number of days needed for the two varieties to reach 50% flowering during the OND season.

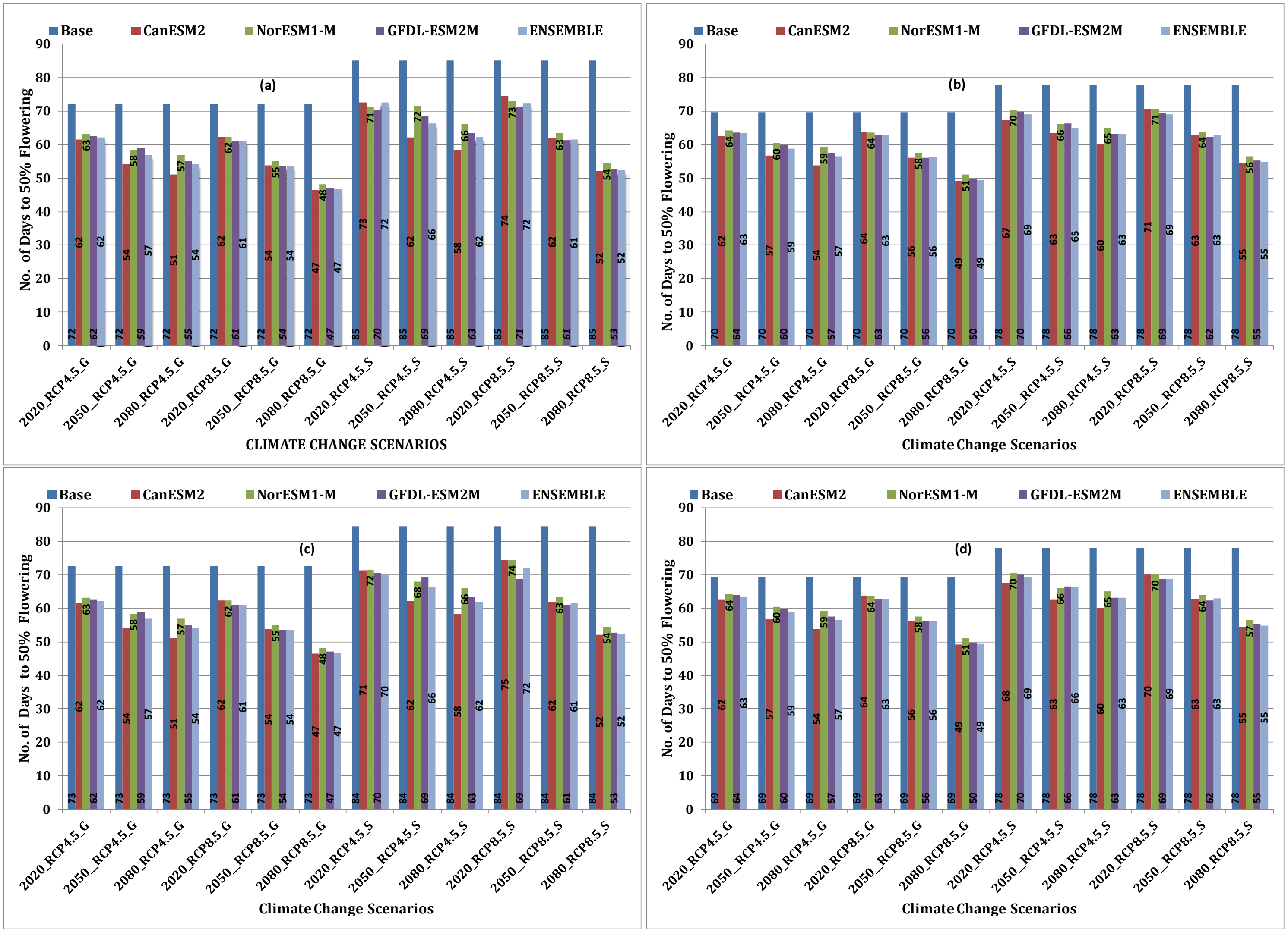

Figure 14: Simulated mean days to 50% flowering for two sorghum cultivars under current (base period) and three future climate scenarios (2020’s, 2050’s and 2080’s) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

Table 36: Percentage mean changes on days to 50% flowering at 0 and 50N fertilizer application rates between baseline and three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars two cultivars during the MAM and OND growing seasons

N-levels (kgha^{-1})	**CORDEX Models**	**GADAM**						**SEREDO**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**CanESM2**	-14.7	-13.4	-24.7	-25.4	-29.1	-35.5	-14.8	-12.5	-26.9	-27.2	-31.4	-38.8
	NorESMI-M	-12.4	-13.5	-19.0	-23.7	-21.0	-33.1	-16.2	-14.4	-15.9	-25.6	-22.5	-36.1
	GFDL-ESM2M	-13.4	-15.2	-18.3	-25.7	-23.6	-34.6	-17.5	-16.2	-19.4	-28.1	-25.6	-37.9
	Ensemble	-13.9	-15.3	-21.2	-25.7	-24.9	-35.2	-14.9	-15.2	-22.3	-27.9	-26.9	-38.6
50N (MAM)	**CanESM2**	-15.2	-14.0	-25.2	-25.9	-29.5	-35.9	-15.5	-11.7	-26.3	-26.6	-30.8	-38.2
	NorESMI-M	-13.1	-14.1	-19.5	-24.2	-21.5	-33.6	-15.3	-11.8	-19.4	-24.9	-21.7	-35.5
	GFDL-ESM2M	-13.9	-15.7	-18.8	-26.2	-24.1	-35.0	-16.5	-18.4	-17.8	-27.5	-24.9	-37.4
	Ensemble	-14.4	-15.8	-21.7	-26.2	-25.4	-35.6	-17.0	-14.4	-21.5	-27.2	-26.6	-38.0
0N (OND)	**CanESM2**	-10.2	-8.2	-18.5	-19.3	-22.6	-29.4	-13.4	-9.2	-18.6	-19.5	-23.0	-30.0
	NorESMI-M	-7.8	-8.6	-13.1	-17.3	-15.1	-26.8	-9.8	-9.2	-15.2	-18.0	-16.4	-27.5
	GFDL-ESM2M	-8.5	-10.0	-14.1	-19.4	-17.4	-28.4	-10.4	-10.9	-14.8	-19.9	-18.8	-29.2
	Ensemble	-8.9	-10.0	-15.5	-19.2	-18.7	-29.1	-11.3	-11.4	-16.4	-19.3	-18.8	-29.7
50N (OND)	**CanESM2**	-9.8	-7.8	-18.1	-18.9	-22.2	-29.1	-13.4	-10.1	-19.6	-19.5	-23.1	-30.0
	NorESMI-M	-7.3	-8.2	-12.7	-16.9	-14.7	-26.4	-9.5	-10.1	-15.2	-18.0	-16.4	-27.5
	GFDL-ESM2M	-7.6	-9.5	-13.7	-19.0	-17.0	-28.0	-10.1	-11.7	-14.7	-20.0	-18.8	-29.2
	Ensemble	-8.4	-9.5	-15.1	-18.8	-18.3	-28.7	-11.2	-11.7	-15.0	-19.3	-18.8	-29.7

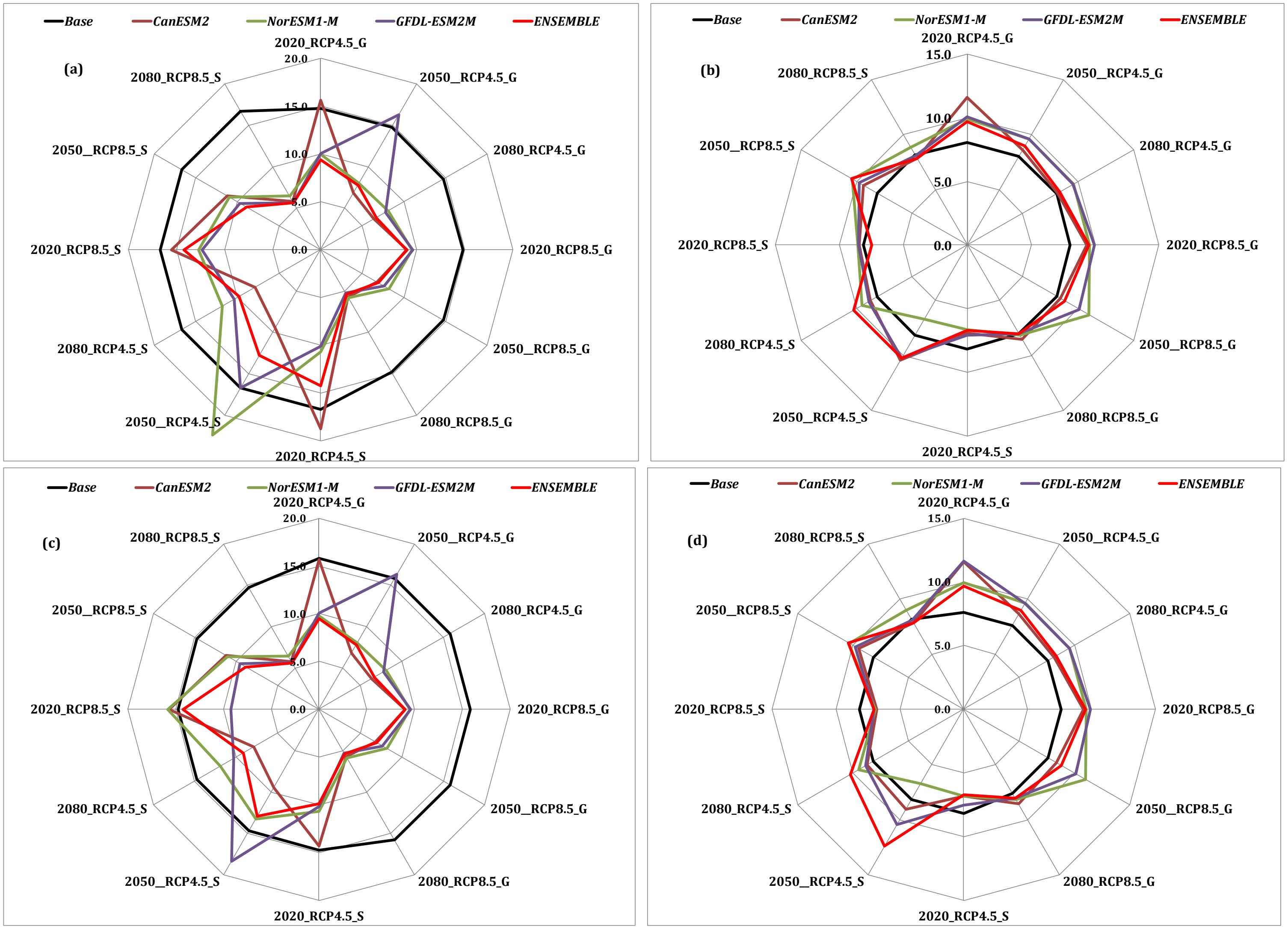

Figure 15: Variability for simulated days to 50% flowering for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

4.6.3 Comparison on Days to Physiological Maturity under Both Current and Future Climate

All GCMs showed that the application of nitrogen fertilizer at 0N and 50N had little or no effect on the days taken by the two sorghum cultivars to reach maturity (Figure 16).

Under current climate the mean number of days taken by the Gadam and Seredo cultivars to reach physiological maturity was 137 and 143 during MAM growing season, for the OND growing season the days were 123 and 126, respectively (Figure 16).

Comparable trends were observed for decline in number of days to maturity as in days to 50% flowering. For the Gadam cultivar, during the MAM (OND) growing seasons, the number of days is reduced by 14 (9), 23 (15) and 27 (19) days for the three future climates; near term, mid century and end century, respectively under the RCP4.5 (Table 37). Under RCP8.5, the days taken by Gadam to reach maturity reduced by 15 (10), 28 (20) and 42 (29) for the near term, mid century and end century, respectively, during MAM (OND) growing seasons (Table 37).

Similar trends were observed in Seredo as in Gadam. Under RCP4.5, the days to maturity were reduced to 126 (115), 118 (110) and 113 (106) days for MAM (OND) seasons for the near term, mid century and end century. On the other hand, under RCP8.5, the number of days were reduced to 126 (115), 112 (105) and 98 (95) for the near term, mid century and end century, respectively, for MAM (OND) seasons.

Both cultivars took considerably more days to reach physiological maturity under current climate than under climate change (Figure 16). The delayed and earlier days to maturity under the baseline climate and changed climate is attributed to slower and quick accumulation of heat units during the growth phase, respectively. It is also evident from the study, that the long season cultivar, Seredo, took more days to mature compared to the short season cultivar, Gadam, under both the current and changed climate (Figure 16). The Seredo cultivar took an average of 2.8 % and 1.3% more days during MAM and OND seasons, respectively under RCP4.5. At the same time, under RCP8.5, the variety took 3% and 1.6% more days during MAM and OND seasons, respectively. It is also evident that both cultivars matured much earlier during the short rains than during the long rains.

As shown in Table 37, all models predict that, if the management and soil properties remain the same, with climate change, the mean changes on number of days to physiological maturity will consistently decrease across the cultivars. All models indicate that under both RCPs, the approach to the end century (2080's) showed a greater decline in the days to maturity when assessed against the current climate (baseline). Shorter growing periods during 2080's under both RCPs could be attributed to higher increase in temperature which resulted in quick accumulation of heat units. This translates into quicker development of the crop and thus earlier maturity as the climate changed. These trends are also consistent with Rinaldi and Luca (2012) in which the end century (2071-2100) showed the greatest shortening in the crop cycle duration.

The decrease in days to physiological maturity in the baseline period revealed in this study is in conformity with other results obtained by other researchers (Chipanshi *et al*., 2003, Dimes *et al.*, 2009; Ventrella *et al.*, 2009; Wang *et al*., 2011; Rinaldi and Luca, 2012). For example, Chipanshi *et al*., 2003, noted that the growing season for sorghum was becoming shorter, the days shrinked by 8 and 4 days in the sand veldt and the hard veldt regions, respectively, in Botswana.

Similar trends on the variability of days to maturity as in days to 50% flowering were noted. The days taken by both varieties to attain physiological maturity is slightly more variable in the baseline period than under climate change during the MAM season (Figure 17a, 17c). However, during the OND season (Figure 17b, 17d), the variability of both current climate and changed climate approximate each other, with the variability being slightly lower under current climate. The models used are able to replicate the variability of the days needed for the two varieties to attain physiological maturity during the OND season. In summary days to physiological maturity depicted less variability as compared to days to 50 % flowering.

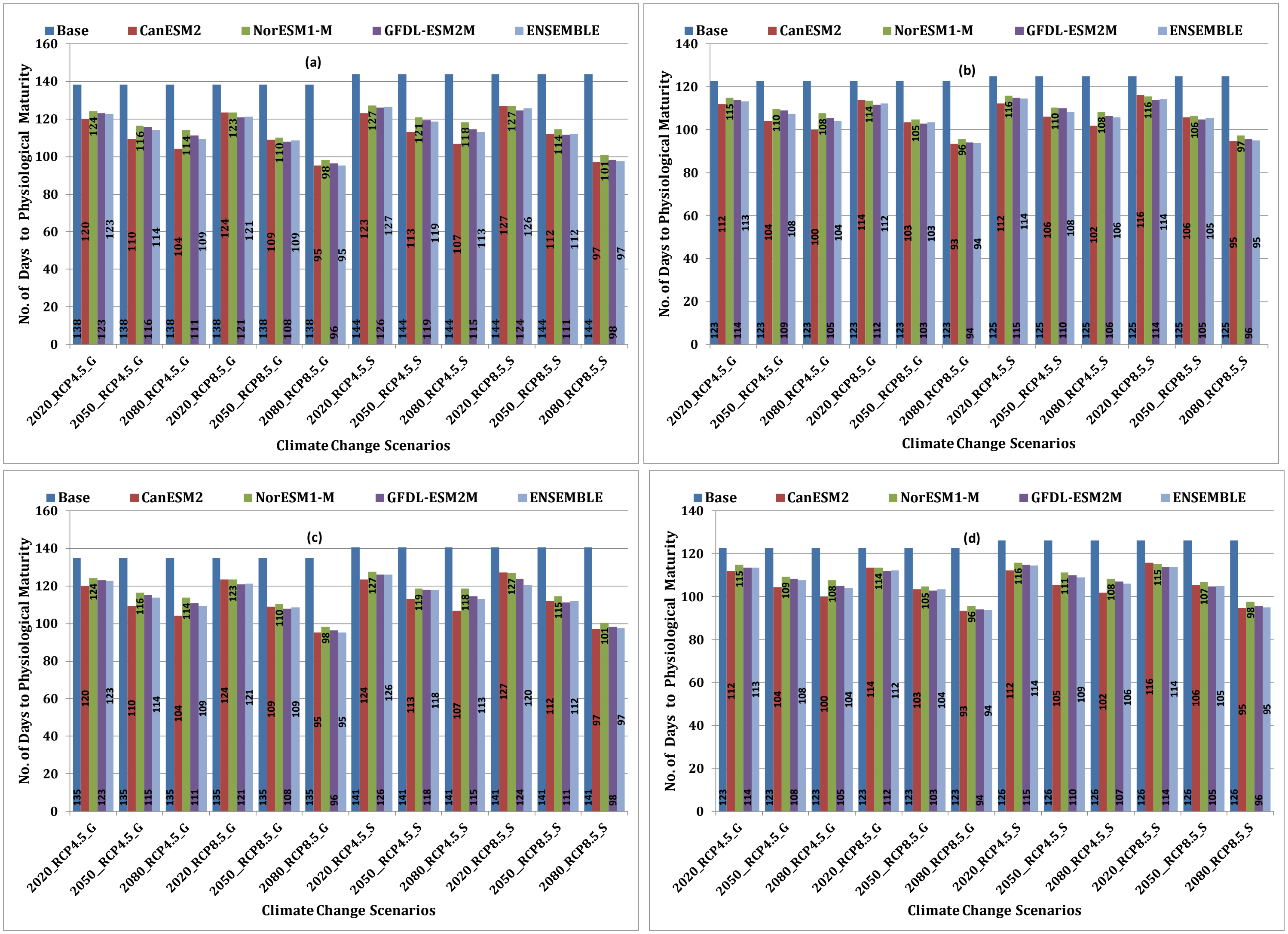

Figure 16: Simulated mean days to physiological maturity for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

Table 37: Percentage mean changes on days to physiological maturity at 0N and 50N fertilizer application rates between baseline and three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars during the MAM and OND growing seasons

N-levels (kgha^{-1})	**CORDEX Models**	**GADAM**						**SEREDO**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**CanESM2**	-13.2	-10.7	-20.9	-21.3	-24.8	-31.2	-14.4	-11.7	-21.3	-22.2	-25.8	-32.5
	NorESMI-M	-10.2	-10.9	-15.9	-20.4	-17.6	-29.1	-11.5	-11.7	-16.0	-20.4	-17.6	-30.0
	GFDL-ESM2M	-11.1	-12.6	-16.5	-22.2	-19.7	-30.5	-12.3	-13.4	-17.1	-22.5	-20.2	-31.7
	Ensemble	-11.3	-12.4	-17.5	-21.6	-21.0	-31.1	-12.0	-12.7	-17.6	-22.1	-21.3	-32.3
50N (MAM)	**CanESM2**	-11.0	-8.4	-18.8	-19.3	-22.9	-29.5	-12.1	-9.4	-19.5	-20.4	-24.0	-30.9
	NorESMI-M	-8.0	-8.6	-13.7	-18.3	-15.6	-27.3	-9.3	-9.7	-15.6	-18.5	-15.7	-28.4
	GFDL-ESM2M	-8.8	-10.4	-14.5	-20.2	-17.9	-28.7	-10.3	-12.0	-16.1	-20.8	-18.4	-30.2
	Ensemble	-9.1	-10.1	-15.6	-19.5	-18.9	-29.3	-10.4	-14.3	-16.2	-20.3	-19.6	-30.7
0N (OND)	**CanESM2**	-8.9	-7.4	-15.1	-15.7	-18.5	-23.9	-10.0	-6.9	-14.9	-15.3	-18.4	-24.0
	NorESMI-M	-6.6	-7.5	-10.8	-14.6	-12.2	-22.0	-7.2	-7.3	-11.6	-14.8	-13.0	-22.0
	GFDL-ESM2M	-7.3	-9.0	-11.2	-16.2	-14.2	-23.3	-7.8	-8.8	-11.9	-15.9	-14.8	-23.2
	Ensemble	-7.7	-8.5	-12.4	-15.8	-15.2	-23.7	-8.3	-8.6	-13.1	-15.6	-15.2	-23.8
50N (OND)	**CanESM2**	-8.6	-7.3	-14.9	-15.6	-18.4	-23.8	-11.1	-8.4	-16.7	-16.4	-19.4	-25.0
	NorESMI-M	-6.4	-7.4	-10.9	-14.7	-12.1	-21.9	-8.2	-8.7	-11.8	-15.6	-14.1	-22.7
	GFDL-ESM2M	-7.3	-8.8	-11.5	-16.1	-14.2	-23.2	-9.0	-9.8	-13.0	-17.0	55.3	-24.3
	Ensemble	-7.5	-8.4	-12.2	-15.5	-15.1	-23.6	-9.4	-10.0	-13.8	-16.8	-16.2	-24.7

Figure 17: Variability for simulated days to physiological maturity for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

4.6.4 Comparison of Biomass under Both Current and Future Climate

All GCMs showed that the application of nitrogen fertilizer at any level had little effect on the biomass, with slightly higher impact during the OND season (Figure 18).

During the MAM season, the biomass accumulated by Seredo under changed climate was more or less equal to that accumulated by Gadam. This shows that no advantage was gained by the long season variety in terms of biomass accumulation. On the other hand, during the OND season, the biomass accumulated by Seredo under climate change is higher than that for Gadam, therefore showing a gain for the long season variety in terms of biomass accumulation (Figure 18).

Under both current and changed climate, the long season variety, Seredo, gives higher above ground biomass than the short season variety Gadam (Figure 18), with slight increase or decrease in biomass for both varieties under climate change (Table 38). Biomass yields of Gadam for the MAM and OND growing season are reduced by 0.5-2.6% and 3-6.3%, respectively under both RCPs with no nutrient application. With application of 50N, there was a slight increase of biomass. For Seredo, biomass yields increased insignificantly under both RCPs except during the OND growing season with no fertilizer application, which depicted a reduction in the biomass (Table 38). The small % changes in biomass reflect little or no effect of changes in rainfall and temperature as represented by RCP4.5 and RCP8.5.

The decline of biomass production is as a result of reduction of crop cycle duration that was brought about by increased temperatures which affected the growth cycle through quicker accumulation of heat units consequently reducing the phenophase duration, hence biomass yield (Attri and Rathore, 2003).

The general decline in biomass, due to impacts related to climate change on sorghum has also been revealed in other studies (Rao *et al.,* 1995, Dimes *et al.,* 2009; Rinaldi and Luca, 2012). For example, Dimes *et al.,* (2009), noted that under combined effects of reduced rainfall and increased temperature the total biomass of sorghum will reduce by 27% in the 21st century.

Variability of biomass is almost the same under both current and changed climate for both varieties during the MAM season (Figure 19a, 19c). However, during the OND season, the variability is slightly higher under current climate as compared to changed climate, with the models showing similar variability of biomass under both RCPs for the three future scenarios (Figure 19b, 19d).

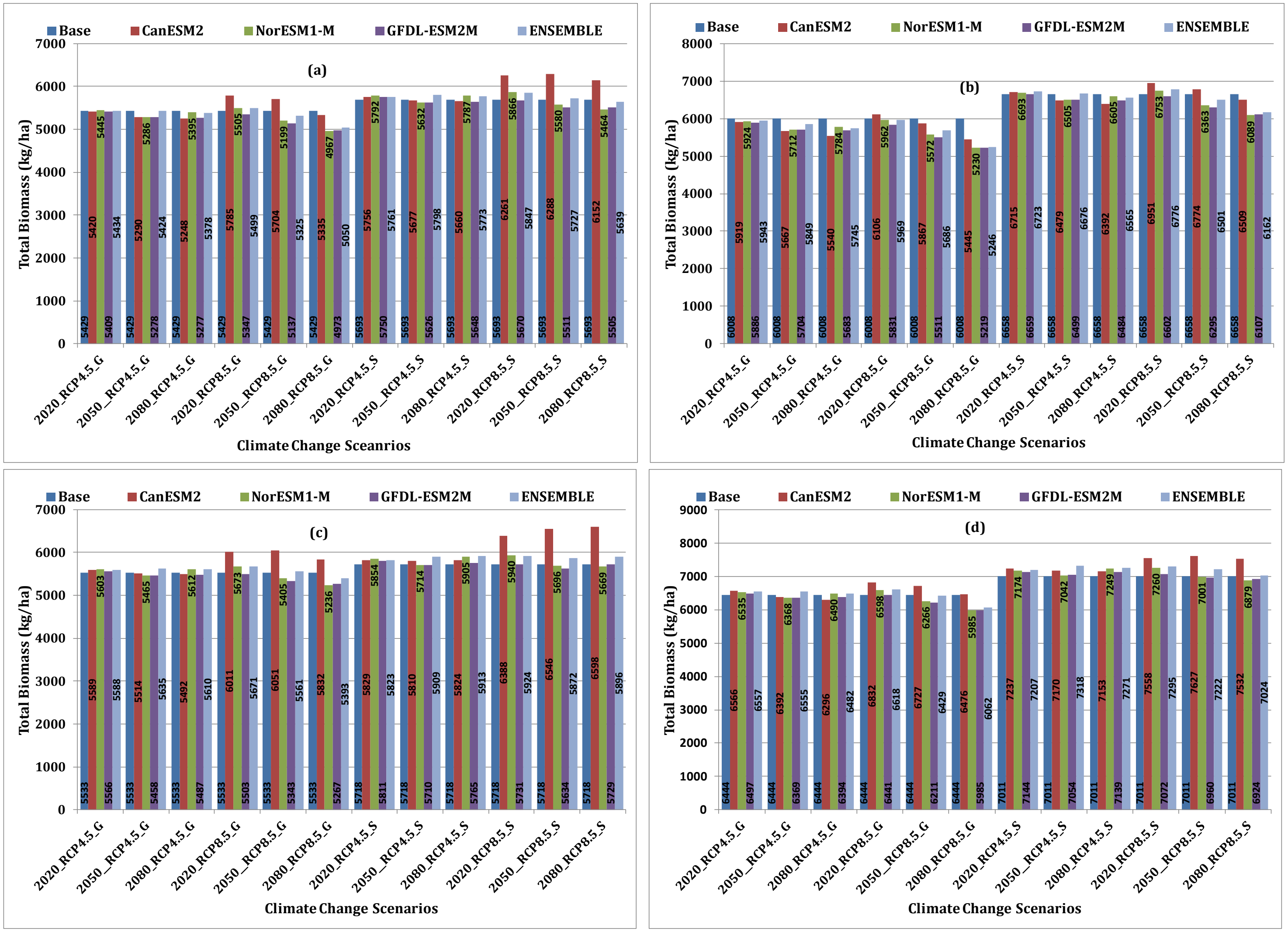

Figure 18: Simulated mean total above ground biomass for two sorghum cultivars under current (base period) and three future climate scenarios (2020’s, 2050’s and 2080’s) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

Table 38: Percentage mean changes on biomass at 0N and 50N fertilizer application rates between baseline and three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars during the MAM and OND growing seasons

N-levels (kgha^{-1})	CORDEX Models	GADAM						SEREDO					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**CanESM2**	-0.2	6.6	-2.6	5.1	-3.3	-1.7	1.1	10.0	-0.3	10.5	-0.6	8.1
	NorESMI-M	0.3	1.4	-2.6	-4.2	-0.6	-8.5	1.7	3.0	-1.1	-2.0	1.7	-4.0
	GFDL-ESM2M	-0.4	-1.5	-2.8	-5.4	-2.8	-8.4	1.0	-0.4	-1.2	-3.2	-0.8	-3.3
	Ensemble	0.1	1.3	-0.1	-1.9	-0.9	-7.0	1.2	2.7	1.8	0.6	1.4	-1.0
50N (MAM)	**CanESM2**	1.0	8.6	-0.4	9.4	-0.8	5.4	1.9	11.7	1.6	14.5	1.9	15.4
	NorESMI-M	1.3	2.5	-1.2	-2.3	1.4	-5.4	2.4	3.9	-0.1	-0.4	3.3	-0.9
	GFDL-ESM2M	0.6	-0.5	-1.4	-3.5	-0.8	-4.8	1.6	0.2	-0.2	-1.5	0.8	0.2
	Ensemble	1.0	2.5	1.8	0.5	1.4	-2.5	1.8	3.6	3.3	2.7	3.4	3.1
0N (OND)	**CanESM2**	-1.5	1.6	-5.7	-2.4	-7.8	-9.4	0.8	4.4	-2.7	1.7	-4.0	-2.2
	NorESMI-M	-1.4	-0.8	-4.9	-7.3	-3.7	-13.0	0.5	1.4	-2.3	-4.4	-0.8	-8.5
	GFDL-ESM2M	-2.0	-2.9	-5.1	-8.3	-5.4	-13.1	0.0	-0.8	-2.4	-5.5	-2.6	-8.3
	Ensemble	-1.1	-0.6	-2.7	-5.4	-4.4	-12.7	1.0	1.8	0.3	-2.4	-1.4	-7.4
50N (OND)	**CanESM2**	1.9	6.0	-0.8	4.4	-2.3	0.5	3.2	7.8	2.3	8.8	2.0	7.4
	NorESMI-M	1.4	2.4	-1.2	-2.8	0.7	-7.1	2.3	3.6	0.4	-0.1	3.4	-1.9
	GFDL-ESM2M	0.8	0.0	-1.2	-3.6	-0.8	-7.1	1.9	0.9	0.6	-0.7	1.8	-1.2
	Ensemble	1.8	2.7	1.7	-0.2	0.6	-5.9	2.8	4.1	4.4	3.0	3.7	0.2

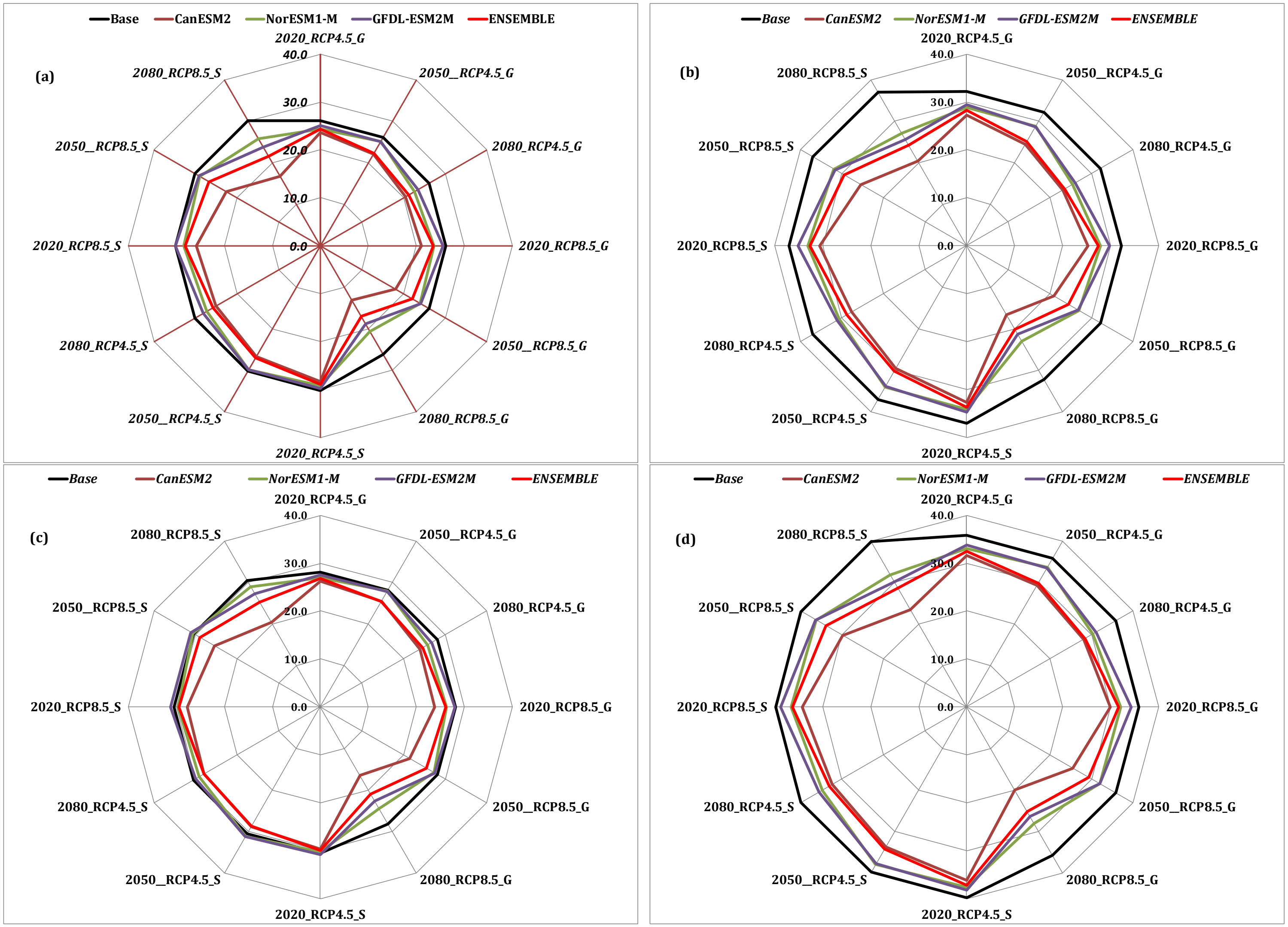

Figure 19: Variability for simulated total above ground biomass for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

4.6.5 Comparison of Sorghum Grain Yield under Both Current and Future Climate

The APSIM-sorghum model indicates that all GCMS predict a brighter future for sorghum growth because continuous increases in sorghum yield are projected from the baseline period to 2080 period under both RCPs. The average mean yields for Gadam under both current and changed climate during the two growing seasons was higher than for Seredo. Sorghum grain yields were elevated under projected climate than under current climate.

All GCMs showed that under current climate the application of nitrogen fertilizer at 50kgha^{-1} had a slight effect on the grain yield for the two sorghum cultivars. The mean grain yield for Gadam (Seredo) cultivars is 2371kgha^{-1} (1809 kgha^{-1}) and 2884 kgha^{-1} (2640 kgha^{-1}) for MAM and OND growing season, respectively under current climate with no nutrient application (Figure 20). However, with application of 50N, sorghum grain yields increased to 2433 kgha^{-1} (1831 kgha^{-1}) and 3146 kgha^{-1} (2819 kgha^{-1}) for MAM and OND growing season, respectively.

Under projected climate change, the grain yield for Gadam are estimated to increase to 2666 kgha^{-1} (2770 kgha^{-1}) and 2807 kgha^{-1} (2973 kgha^{-1}) under RCP4.5 (8.5) with the application of 0N and 50N, respectively during the MAM season. During the OND season, the grain yield for the Gadam are estimated to increase to 3065 kgha^{-1} (3092 kgha^{-1}) and 3501 Kgha^{-1} (3580 kgha^{-1}) with the application of 0N and 50N, respectively, under RCP4.5 (8.5) (Figure 20).

For the Seredo, the grain yield increased to 2230kgha^{-1} (2436 kgha^{-1}) and 2288kgha^{-1} (2544 kgha^{-1}) under RCP4.5 (8.5) with the application of 0N and 50N, respectively during the MAM season. During the OND season, the grain yield increased to 2979 kgha^{-1} (3058 kgha^{-1}) and 3277 kgha^{-1} (3431 kgha^{-1}) with the application of 0N and 50N, respectively, under RCP4.5 (8.5). The grain yield for the long season cultivar under climate change approximates that of the short season cultivar, under baseline climate (Figure 20).

During the MAM growing season, sorghum grain yields were projected to increase. The increase varied between 9.3% and 19.2% in the near term, 12.2% and 34.1% in the mid-century and 15.9% and 50.6% at the end of the century with no fertilizer application (Table 39). However, with 50N application the grain yield slightly increased varying between 11.1% and 21.8%, between 15.3% and 37.5% and between 19.8% and 58.2% in the near term, mid-century and towards end of the century, respectively.

During the OND growing season, sorghum yields were also projected to increase. The increase varied between 5.8% and 10.9% in the near term, 6.0% and 15.9% in the mid-century and 7.1% and 20.6% at the end of the century with no fertilizer application (Table 39). However, with 50N application the grain yield slightly increased varying between 8.8% and 13.3%, between 11.5% and 21.4% and between 13.6% and 30.6% in the near term, mid-century and end of the century, respectively.

The magnitude of change in the yield was higher for Seredo than for Gadam. Highest values were also noted in MAM especially towards the end century (2070-2099), with values of up to 85.3% (Table 39). The CanESM2 model predicts the highest future sorghum yield if the management options remain the same as those for the baseline period, whereas GFDL-ESM2M predicts the lowest yield for the future.

Increased sorghum grain yields revealed by nearly all GCMs under the two RCPs, is attributed to increase in both projected temperatures and rainfall which tend to create conducive environment for the growth of sorghum. Optimum levels of Nitrogen fertilizer application have also indicated increase in grain yield. The study results are consistent with the observations by Kaiser *et al.*, 1993; Chipanshi *et al.*, 2003; Breisinger *et al.*, 2011; Chijioke *et al*., 2011; Turner and Rao, 2013; Gwimbi *et al*., 2013; Msongaleli *et al*., 2015), which showed increase in sorghum grain yields under changed climate in specific regions. However, the results are in contrast with those of Chen *et a*l., 2004; Butt *et al.*, 2005; IPCC, 2007; Dimes *et al.*, 2009; Nelson *et al.*, 2009; Tingem *et al.*, 2009; Srivastava *et al.*, 2010. For example IPCC (2007) indicated that potential yield in the ASALs will decrease with climate change.

Under current climate, yields of both Gadam and Seredo cultivars are more variable compared to changed climate (Figure 21) during the two growing seasons (MAM and OND). Larger variations in the sorghum grain yield are simulated under GFDL-ESM2M, whereas CanESM2 model predicts considerable variations in the grain yield. When comparing the three scenarios independently for the two RCPs the long season variety, Seredo, depicted slightly higher variability as compared to the short season variety. From the study it can be deduced that the sorghum grain yield showed greater variability as compared to the other variables (days to 50% flowering, days to physiological maturity and total above ground biomass).

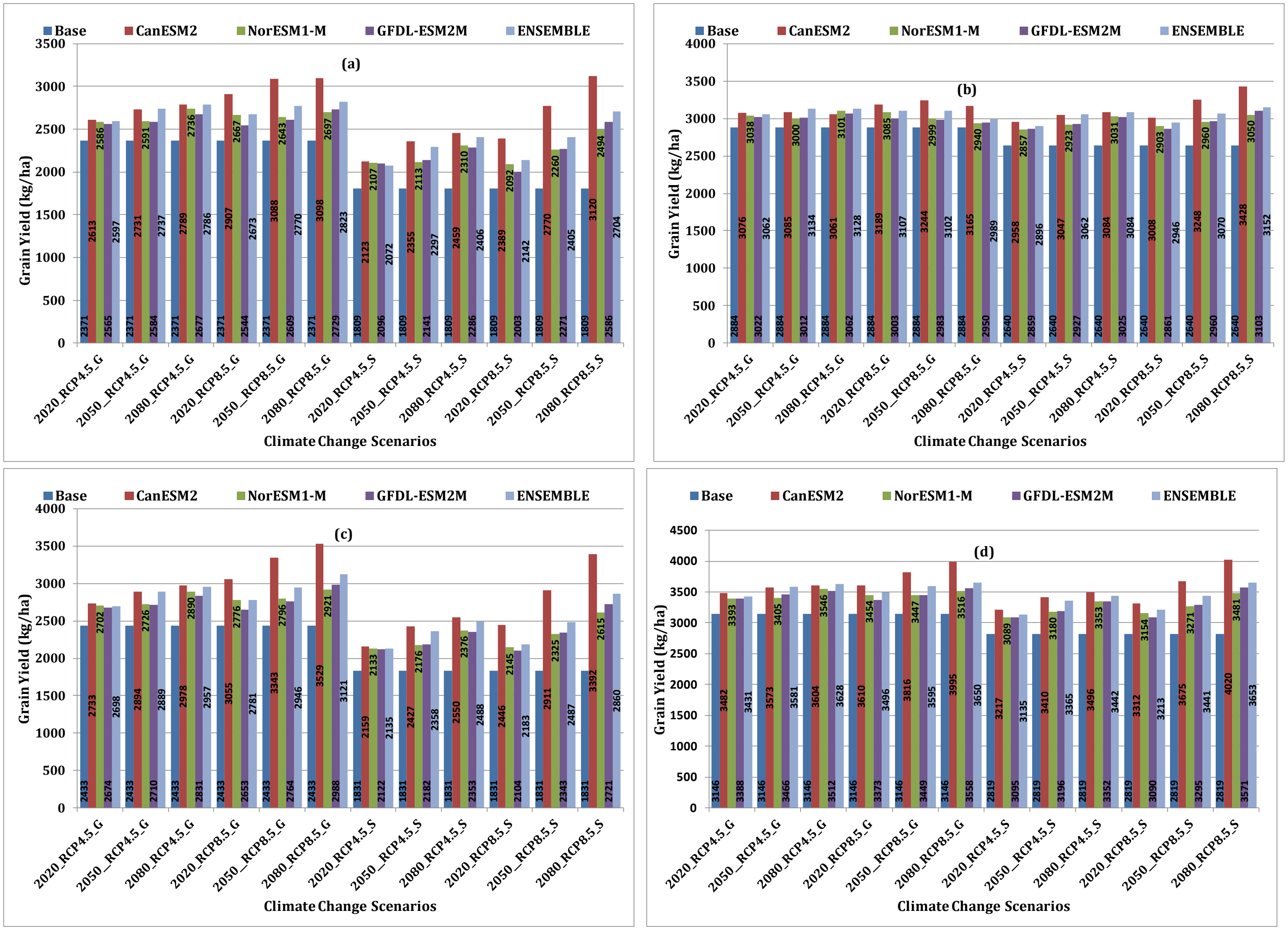

Figure 20: Simulated mean grain yield for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

Table 39: Percentage mean changes on grain yield at 0N and 50N fertilizer application rates between baseline and three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars during the MAM and OND growing season

N-levels (kgha-1)	**CORDEX Models**	**GADAM**						**SEREDO**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**CanESM2**	10.2	22.6	15.2	30.3	17.7	30.7	17.4	32.0	30.2	53.1	35.9	72.4
	NorESMI-M	9.1	12.5	9.3	11.5	15.4	13.8	16.5	15.6	16.8	24.9	27.7	37.8
	GFDL-ESM2M	8.2	7.3	9.0	10.0	12.9	15.1	15.8	10.7	18.3	25.5	26.3	42.9
	Ensemble	9.6	12.7	15.4	16.8	17.5	19.1	14.5	18.4	27.0	32.9	33.0	49.4
50N (MAM)	**CanESM2**	12.3	25.5	19.0	37.4	22.4	45.0	17.9	33.6	32.6	59.0	39.3	85.3
	NorESMI-M	11.1	14.1	12.0	14.9	18.8	20.1	16.5	17.1	18.8	27.0	29.7	42.8
	GFDL-ESM2M	9.9	9.0	11.4	13.6	16.4	22.8	15.9	14.9	19.2	28.0	28.5	48.6
	Ensemble	10.9	14.3	18.7	21.1	21.5	28.3	16.6	19.2	28.8	35.8	35.9	56.2
0N (OND)	**CanESM2**	6.7	10.6	6.9	12.5	6.1	9.7	12.0	13.9	15.4	23.0	16.8	29.8
	NorESMI-M	5.3	7.0	4.0	4.0	7.5	1.9	8.2	10.0	10.7	12.1	14.8	15.5
	GFDL-ESM2M	4.8	4.1	4.4	3.4	6.2	2.3	8.3	8.4	10.9	12.1	14.6	17.5
	Ensemble	6.2	7.7	8.7	7.5	8.4	3.6	9.7	11.6	16.0	16.3	16.8	19.4
50N (OND)	**CanESM2**	10.7	14.7	13.6	21.3	14.6	27.0	14.1	17.5	21.0	30.4	24.0	42.6
	NorESMI-M	7.8	9.8	8.2	9.6	12.7	11.8	9.6	11.9	12.8	16.0	19.0	23.5
	GFDL-ESM2M	7.7	7.2	10.2	9.6	11.6	13.1	9.8	9.6	13.4	16.9	18.9	26.7
	Ensemble	9.1	11.1	13.8	14.3	15.3	16.0	11.2	14.0	19.4	22.1	22.1	29.6

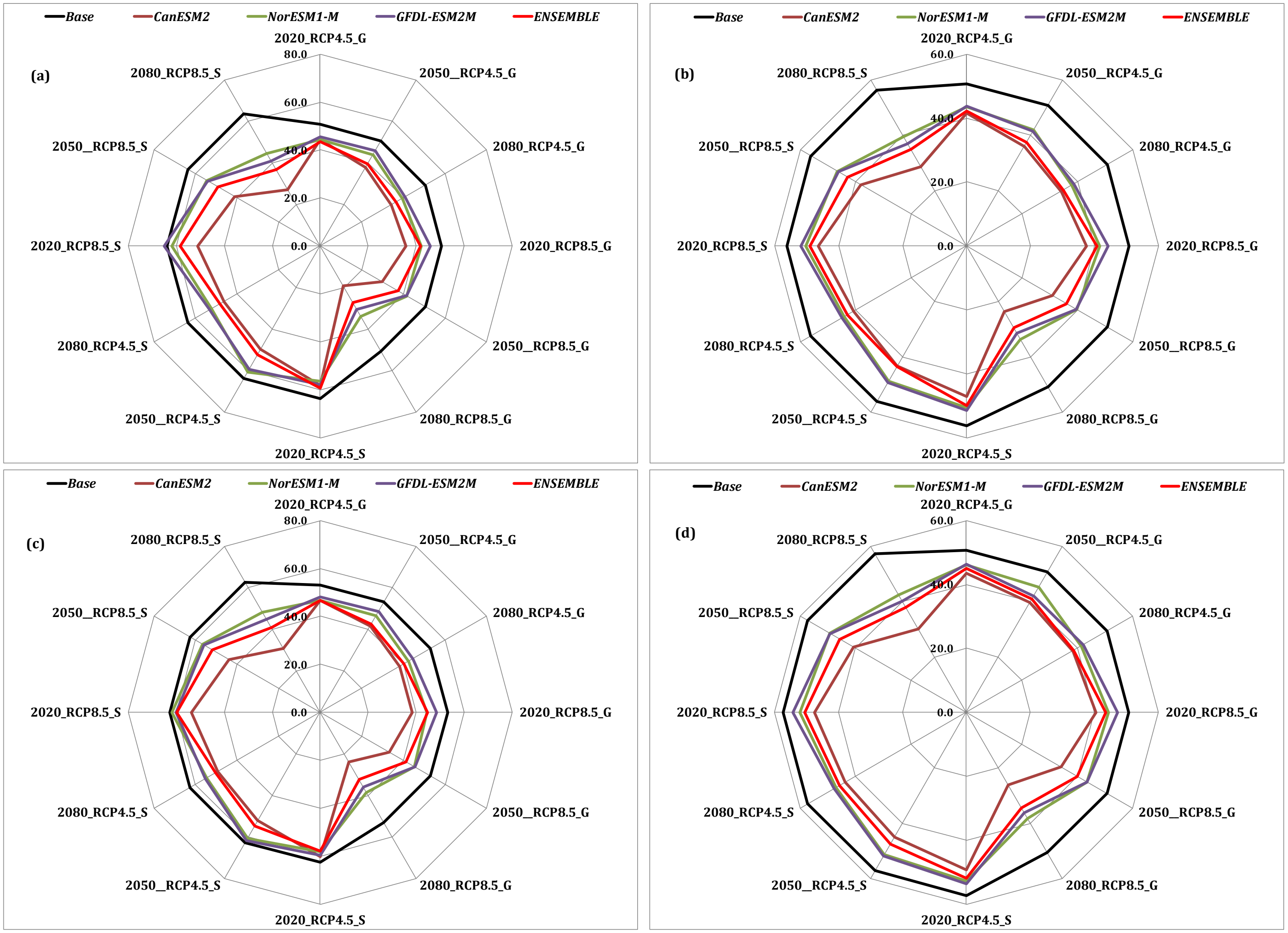

Figure 21: Variability for simulated grain yield for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. (a), (b), (c) and (d) represents application of 0N during the MAM growing season, 0N during the OND growing season, 50N during the MAM growing season and 50N during the OND growing season, respectively.

4.7 Effect of Different Agronomic Management Practices

The effect of different fertilizer application rates and the plant population on the productivity of sorghum was analyzed using APSIM-sorghum model. Farmers in the region grow sorghum with an inter row spacing of 75 cm and intra row spacing of 20cm, giving a total plant population of 66,666 plants ha^{-1} (75cm by 20cm). In this study two different treatments of plant populations combined with two levels of inorganic fertilizer application rates were simulated so as to find out the effect of reducing the plant population to 53,333 plants ha^{-1} (75cm by 25cm) and increasing the plant population to 88,888 plants ha^{-1} (75cm by 15 cm).

4.7.1 Effect of Plant Population on Days to 50% Flowering

Increasing intra and inter plant spacing (increasing the plant population) resulted to increased number of days to 50% flowering for both cultivars under both the present and changed climate as compared to the standard practice (66,666 plants ha^{-1}) (Table 40). The percentage change was relatively higher during the MAM growing season and this could be attributed to the variability of the MAM seasonal rainfall thus increasing the plant competition for the available growth resources (soil moisture, soil nutrients, and light) and resulting to sorghum plants flowering late.

For the OND growing season the percentage change is relatively lower. This may be because the season is less variable thus plant competition for the available resources is slightly reduced. Seredo cultivar showed relatively higher percentage change as compared to Gadam cultivar, this could be attributed to the fact that Seredo cultivar is a long season cultivar and thus it takes more days to reach 50% flowering as compared to Gadam which is a short season cultivar (Table 40). On the other hand, early flowering was noted with reduced plant population (53,333 plants ha^{-1}) as compared to the standard practice. This could be attributed to comfortable growth due to sufficient growth resources which resulted in early flowering (Table 40). There was no difference between the percentage changes in days to 50% flowering with the 0 and 50N kgha^{-1} for both the low and high plant population. Compatible results were obtained by Mekdad and Rady 2016, who reported that increasing plant population and decreasing plant population increased and decreased the days to 50% flowering, respectively.

Across the cultivars, the days to 50% flowering was less variable (less than 20%) for both plant populations during both MAM and OND growing seasons under both the base period and changed climate (Figures 22 and 23). During the OND growing season, the variability of the base period was slightly lower as compared to the changed climate, with the high plant population. For low plant population, the variability was slightly higher under changed climate as compared to base period especially for the Gadam cultivar. Little or no change was noted on the variability with the application of inorganic fertilizer.

Table 40: Percentage mean changes on days to 50% flowering at 0N and 50N fertilizer application rates between population of 66,666 plants ha^{-1} and two different plant populations 53,333 plants ha^{-1} and 88,888 plants ha^{-1} for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars during the MAM and OND growing seasons

N-levels (kgha^{-1})	**CORDEX Models**	**88,888 plants ha^{-1}**						**53,333 plants ha^{-1}**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
GADAM													
0N /50N (MAM)	**Present**	1.4	1.4	1.4	1.4	1.4	1.4	-2.8	-2.8	-2.8	-2.8	-2.8	-2.8
	CanESM2	1.6	0.0	0.0	0.0	2.0	0.0	-1.6	0.0	0.0	0.0	-1.9	0.0
	NorESMI-M	1.6	0.0	0.0	1.8	0.0	0.0	-1.6	0.0	0.0	0.0	0.0	0.0
	GFDL-ESM2M	1.6	0.0	1.7	1.9	0.0	0.0	-1.6	-1.6	-1.7	0.0	-1.8	0.0
	Ensemble	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0N/50N (0ND)	**Present**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	CanESM2	0.0	1.6	0.0	0.0	0.0	0.0	-1.6	0.0	0.0	0.0	0.0	0.0
	NorESMI-M	0.0	0.0	0.0	0.0	0.0	0.0	-1.5	0.0	-1.7	0.0	0.0	0.0
	GFDL-ESM2M	1.6	1.6	0.0	0.0	0.0	0.0	0.0	-1.6	0.0	-1.8	0.0	0.0
	Ensemble	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SEREDO													
0N/50N (MAM)	**Present**	3.5	3.5	3.5	3.5	3.5	3.5	-5.8	-5.8	-5.8	-5.8	-5.8	-5.8
	CanESM2	1.4	1.4	1.6	1.6	0.0	0.0	-4.1	-1.4	0.0	-1.6	-1.7	0.0
	NorESMI-M	2.8	0.0	1.4	1.6	4.5	0.0	-1.4	0.0	-5.6	-1.6	-1.5	0.0
	GFDL-ESM2M	2.8	1.4	1.4	1.6	1.6	1.9	-1.4	0.0	-2.9	-1.6	-1.6	0.0
	Ensemble	0.0	1.4	1.5	1.6	1.6	0.0	0.0	-1.4	-3.0	-1.6	-1.6	0.0
0N/50N (OND)	**Present**	1.3	1.3	1.3	1.3	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0
	CanESM2	0.0	1.4	1.6	0.0	1.7	0.0	0.0	-1.4	0.0	0.0	0.0	0.0
	NorESMI-M	1.4	0.0	0.0	1.6	0.0	0.0	-1.4	0.0	-1.5	-1.6	0.0	0.0
	GFDL-ESM2M	0.0	1.4	1.5	0.0	1.6	0.0	-1.4	0.0	0.0	0.0	-1.6	0.0
	Ensemble	0.5	1.3	0.5	1.0	0.8	0.0	-0.7	-1.0	-1.0	-0.5	-0.8	0.0

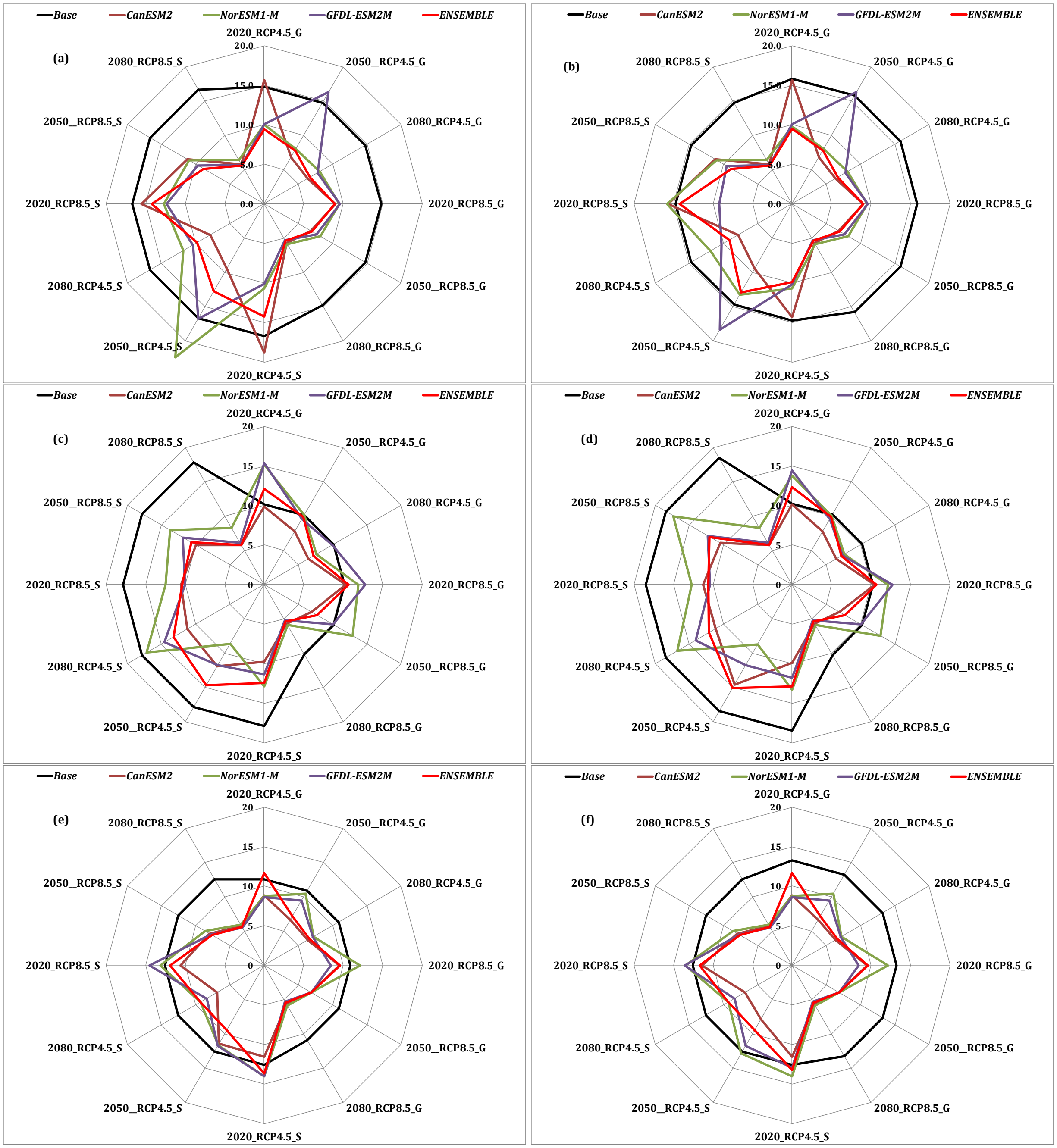

Figure 22 : Variability for simulated days to 50% flowering for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the MAM growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively.

Figure 23: Variability for simulated days to 50% flowering for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the OND growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively.

4.7.2 Effect of Plant Population on Days to Physiological Maturity

Across the GCMs delayed days to maturity for both cultivars were recorded for the increased plant population, nevertheless early maturity was noted for the decreased plant population. Generally, days to physiological maturity increased in response to increasing plant population from 66,666 to 88,888 plants per hectare and decreased in response to decreasing plant population from 66,666 to 53,333 plants per hectare (Table 41). The percentage increase or decrease was higher for Seredo than for Gadam.

The percentage increase in the days to physiological maturity in high plant populations could be due to the fact that at higher plant populations the competition for the available growth resources (soil moisture, nutrient and light) is higher as compared to the lower plant population resulting to an extended vegetative growth period.

During the MAM growing season both high and low plant population showed that variability on the days to maturity was slightly higher for the base period as compared to the changed climate (Figure 24). For the high plant population the number of days to attain physiological maturity for Seredo cultivar increased under both current and changed climate, but this decreased with fertilizer application. For the Gadam cultivar, the variability was reduced both at 0N and 50N kgha^{-1}. At low plant population the variability of both cultivars under both the base period and the changed climate was reduced most especially with no fertilizer application.

During the OND season, the variability is lower (less than 7%) for both cultivars for both climates (Figure 25). The effect of increasing or decreasing the plant population was negligible for both climates.

4.7.3 Effect of Plant Population on Above Ground Biomass

Comparing the above ground biomass weight for the standard practical and the different plant populations, an increase in the biomass was noted for the highest plant population (88,888 plants ha^{-1}) and a decrease was noted for the lowest plant population (55,333 plants ha^{-1}) for both cultivars and across the GCMs (Tables 42 and 43). Increase plant population may have contributed to increase photosynthetically active radiation (PAR) due to greater leaf area indices under higher plant densities. The percentage change in the total above ground biomass was relatively higher during short rainfall season as compared to the long rainfall season.

The percentage increase in above ground biomass weight due to increased plant population per hectare established in this study is in agreement with other findings. Getachew (2014); Soleymani *et al*., (2011); Buah and Mwinkaara (2009) and Tabo *et al*. (2002) who reported an increase in above ground biomass with increasing plant population per hectare.

The percentage change in total above ground biomass was greater with fertilizer application (50 kg N/ha) compared to the control (0 kg N/ha). The increase in above ground biomass with fertilizer application over the control may be as result of increase in plant height, leaf area and number of leaves.

Considering both MAM and OND growing seasons, the base period showed greater variations in biomass yield as compared to the changed climate for the two cultivars studied (Figures 26 and 27). The variations of biomass increased with increase in plant population and decreased with decrease in plant population. Increased variability was noted with the application of inorganic fertilizer.

Table 41: Percentage mean changes on days to Physiological maturity at 0N and 50N fertilizer application rates between population of 66,666 plants ha^{-1} and two different plant populations 53,333 plants ha^{-1} and 88,888 plants ha^{-1} for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the two cultivars during the MAM and OND growing seasons

N-levels (kgha^{-1})	CORDEX Models	88,888 plants ha^{-1}						53,333 plants ha^{-1}					
		2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
GADAM													
0N/50N (MAM)	**Present**	0.7	0.7	0.7	0.7	0.7	0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
	CanESM2	0.0	0.8	0.0	0.9	0.0	0.0	-0.8	0.0	0.0	0.0	0.0	0.0
	NorESMI-M	0.8	0.8	0.9	0.0	0.0	0.0	-0.8	-0.8	0.0	0.0	0.0	0.0
	GFDL-ESM2M	0.8	0.8	0.0	0.9	0.0	0.0	-0.8	0.0	-0.9	0.0	0.0	0.0
	Ensemble	1.6	0.8	0.0	0.9	0.0	0.0	0.0	-0.8	0.0	0.0	0.0	0.0
0N/50N (OND)	**Present**	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
	CanESM2	0.0	0.9	0.0	0.0	1.0	0.0	0.0	0.0	-1.0	0.0	0.0	0.0
	NorESMI-M	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GFDL-ESM2M	0.0	0.9	0.0	1.0	0.0	0.0	-0.9	0.0	-0.9	0.0	-0.9	0.0
	Ensemble	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.9	0.0	0.0	-1.0	0.0
SEREDO													
0N/50N (MAM)	**Present**	3.5	3.5	3.5	3.5	3.5	3.5	-2.8	-2.8	-2.8	-2.8	-2.8	-2.8
	CanESM2	1.6	0.8	0.9	0.9	0.9	0.0	-0.8	-0.8	-0.9	0.0	0.0	0.0
	NorESMI-M	1.6	1.6	0.0	0.9	0.0	0.0	-0.8	-1.6	-0.8	-0.9	-0.8	0.0
	GFDL-ESM2M	0.8	1.6	0.0	0.9	0.9	0.0	-0.8	-0.8	0.0	-0.9	-0.9	-1.0
	Ensemble	0.8	0.8	0.0	0.9	0.9	0.0	-0.8	-0.8	-0.8	0.0	-0.9	0.0
0N/50N (OND)	**Present**	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
	CanESM2	0.0	0.0	0.9	0.0	0.0	0.0	0.0	-0.9	0.0	0.0	0.0	0.0
	NorESMI-M	0.9	0.0	0.0	0.9	2.8	0.0	0.0	-0.9	-0.9	-0.9	-0.9	0.0
	GFDL-ESM2M	0.9	0.9	0.9	1.0	0.9	1.0	0.0	0.0	0.0	0.0	-0.9	0.0
	Ensemble	0.9	0.0	0.9	0.0	0.0	0.0	0.0	-0.9	0.9	0.0	0.0	-1.0

Table 42: Percentage mean changes on total above ground biomass at 0N and 50N fertilizer application rates between population of 66,666 plants ha^{-1} and two different plant populations 53,333 plants ha^{-1} and 88,888 plants ha^{-1} for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the Gadam cultivar during the MAM and OND growing seasons

N-levels (kgha^{-1})	CORDEX Models	88,888 plants ha^{-1}						53,333 plants ha^{-1}					
		2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**Present**	6.4	6.4	6.4	6.4	6.4	6.4	-7.4	-7.4	-7.4	-7.4	-7.4	-7.4
	CanESM2	6.2	7.2	6.0	6.9	5.6	6.4	-7.9	-9.0	-7.8	-9.2	-7.8	-9.0
	NorESMI-M	6.4	6.4	6.2	6.1	6.2	5.7	-7.9	-8.0	-7.7	-7.7	-8.1	-7.9
	GFDL-ESM2M	6.3	6.2	6.1	6.0	6.0	5.5	-7.8	-7.7	-7.7	-7.5	-7.7	-7.7
	Ensemble	6.2	6.3	6.1	6.0	5.9	5.7	-7.8	-8.0	-7.9	-7.8	-7.9	-8.0
50N (MAM)	**Present**	6.0	6.0	6.0	6.0	6.0	6.0	-7.2	-7.2	-7.2	-7.2	-7.2	-7.2
	CanESM2	6.4	7.4	6.4	7.4	6.0	6.9	-8.0	-9.2	-8.5	-10.1	-8.3	-10.1
	NorESMI-M	6.4	6.6	6.4	6.5	6.6	6.3	-8.1	-8.2	-8.0	-8.3	-8.6	-8.7
	GFDL-ESM2M	6.4	6.3	6.4	6.3	6.3	6.0	-7.9	-7.8	-7.9	-8.2	-8.2	-8.7
	Ensemble	6.3	6.5	6.4	6.3	6.3	6.1	-7.9	-8.1	-8.3	-8.5	-8.4	-9.3
0N (OND)	**Present**	9.5	9.5	9.5	9.5	9.5	9.5	-10.2	-10.2	-10.2	-10.2	-10.2	-10.2
	CanESM2	9.2	9.6	8.9	9.1	8.8	9.2	-10.4	-10.4	-10.1	-10.4	-9.7	-9.8
	NorESMI-M	9.1	9.2	9.1	8.9	9.2	8.9	-10.2	-10.2	-9.8	-9.9	-10.2	-9.5
	GFDL-ESM2M	9.0	9.0	9.1	8.6	9.0	9.2	-10.3	-10.2	-9.8	-9.9	-9.9	-9.4
	Ensemble	9.2	9.3	9.2	8.8	8.8	9.1	-10.4	-10.4	-10.3	-10.2	-10.2	-9.4
50N (OND)	**Present**	10.9	10.9	10.9	10.9	10.9	10.9	-11.6	-11.6	-11.6	-11.6	-11.6	-11.6
	CanESM2	11.1	11.4	10.9	11.0	10.6	10.0	-12.1	-12.4	-12.7	-12.7	-12.4	-13.7
	NorESMI-M	11.0	11.1	11.0	11.1	11.2	10.8	-12.1	-12.1	-12.2	-12.6	-12.5	-13.2
	GFDL-ESM2M	10.9	10.8	11.0	10.8	11.0	10.9	-12.0	-12.0	-12.3	-12.6	-12.5	-13.1
	Ensemble	11.1	11.2	11.0	10.8	10.8	10.4	-11.9	-12.0	-12.3	-12.8	-12.5	-13.0

Table 43: Percentage mean changes on total above ground biomass at 0N and 50N fertilizer application rates between population of 66,666 plants ha^{-1} and two different plant populations 53,333 plants ha^{-1} and 88,888 plants ha^{-1} for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the Seredo cultivar during the MAM and OND growing seasons

N-levels (kgha^{-1})	**CORDEX Models**	**88,888 plants ha^{-1}**						**53,333 plants ha^{-1}**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**Present**	4.1	4.1	4.1	4.1	4.1	4.1	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
	CanESM2	4.0	4.4	3.7	3.7	3.5	2.8	-5.4	-6.2	-5.4	-5.9	-5.2	-5.8
	NorESMI-M	4.1	4.2	3.9	3.8	3.8	3.4	-5.5	-5.6	-5.4	-5.4	-5.6	-5.2
	GFDL-ESM2M	4.1	4.0	3.8	3.7	3.8	3.2	-5.5	-5.4	-5.4	-5.3	-5.4	-5.0
	Ensemble	4.1	4.1	3.7	3.7	3.7	3.1	-5.5	-5.6	-5.5	-5.4	-5.3	-5.2
50N (MAM)	**Present**	4.6	4.6	4.6	4.6	4.6	4.6	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0
	CanESM2	4.6	5.3	4.5	5.1	4.2	4.3	-5.3	-6.3	-5.7	-6.7	-5.8	-7.2
	NorESMI-M	4.6	4.7	4.6	4.5	4.7	4.3	-5.3	-5.5	-5.4	-5.6	-5.8	-6.0
	GFDL-ESM2M	4.6	4.5	4.5	4.3	4.5	4.1	-5.3	-5.2	-5.3	-5.6	-5.6	-6.0
	Ensemble	4.5	4.7	4.5	4.5	4.4	4.1	-5.3	-5.4	-5.6	-5.8	-5.7	-6.2
0N (OND)	**Present**	7.0	7.0	7.0	7.0	7.0	7.0	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8
	CanESM2	6.0	6.2	5.5	5.5	5.4	4.6	-8.6	-8.7	-8.2	-8.4	-8.0	-7.8
	NorESMI-M	6.2	6.1	5.4	5.3	5.5	5.2	-8.5	-8.7	-8.3	-8.0	-8.4	-8.0
	GFDL-ESM2M	6.0	5.8	5.4	5.3	5.5	5.1	-8.5	-8.5	-8.2	-8.0	-8.1	-8.0
	Ensemble	6.1	5.9	5.5	5.5	5.5	5.1	-8.6	-8.7	-8.4	-8.2	-8.2	-7.9
50N (OND)	**Present**	9.5	9.5	9.5	9.5	9.5	9.5	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9
	CanESM2	9.7	10.2	9.6	9.5	9.1	7.9	-10.5	-10.5	-10.5	-10.5	-10.4	-10.8
	NorESMI-M	9.7	9.7	9.8	9.6	9.7	8.3	-10.3	-10.4	-10.1	-10.1	-10.6	-10.8
	GFDL-ESM2M	9.7	10.0	9.6	9.4	9.5	7.8	-10.3	-10.0	-10.1	-10.2	-10.2	-10.7
	Ensemble	9.7	9.7	9.7	9.5	9.6	7.7	-10.4	-10.4	-10.6	-10.5	-10.4	-10.8

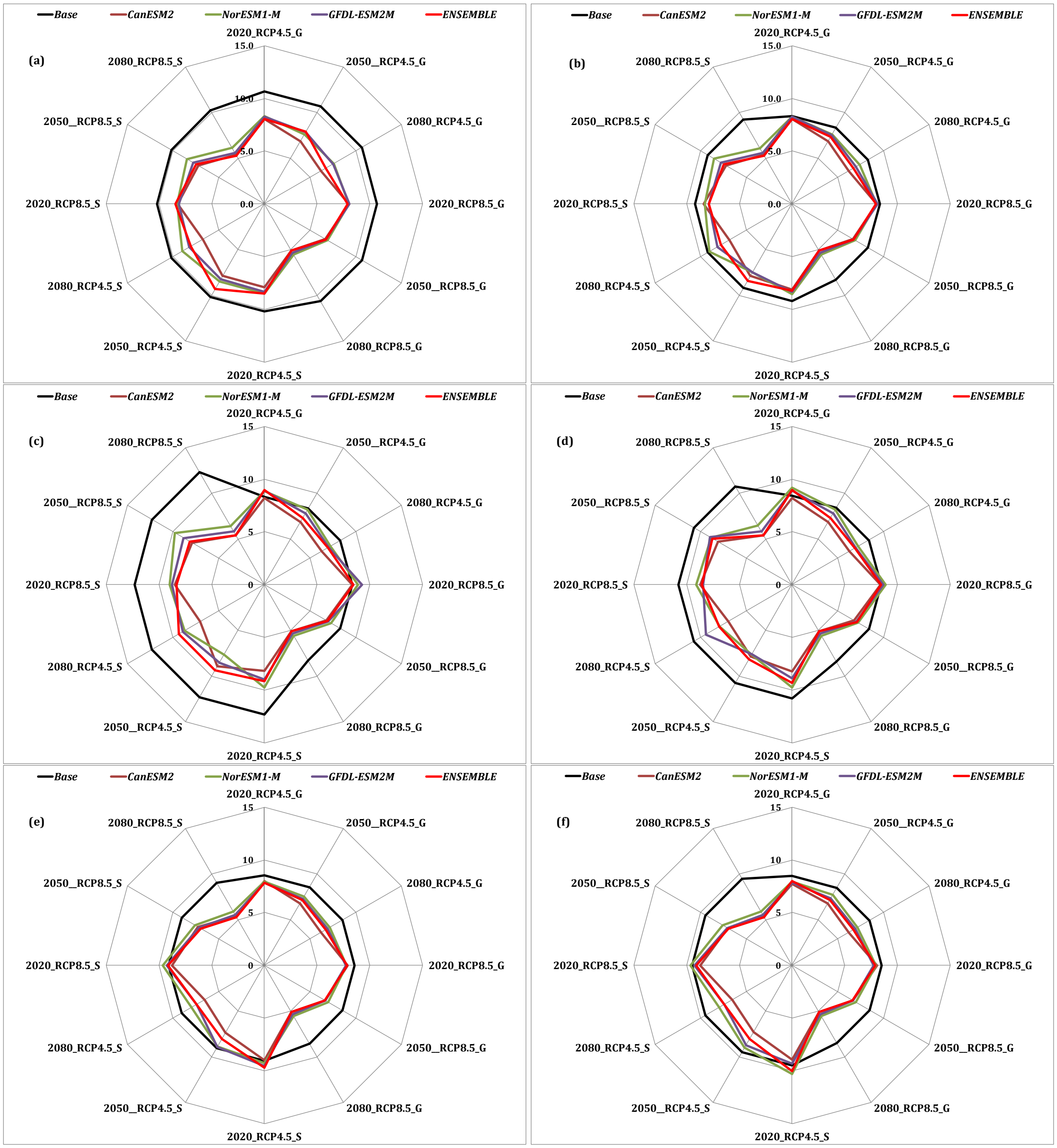

Figure 24: Variability for simulated days to physiological maturity for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the MAM growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively

Figure 25: Variability for simulated days to physiological maturity for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the OND growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively

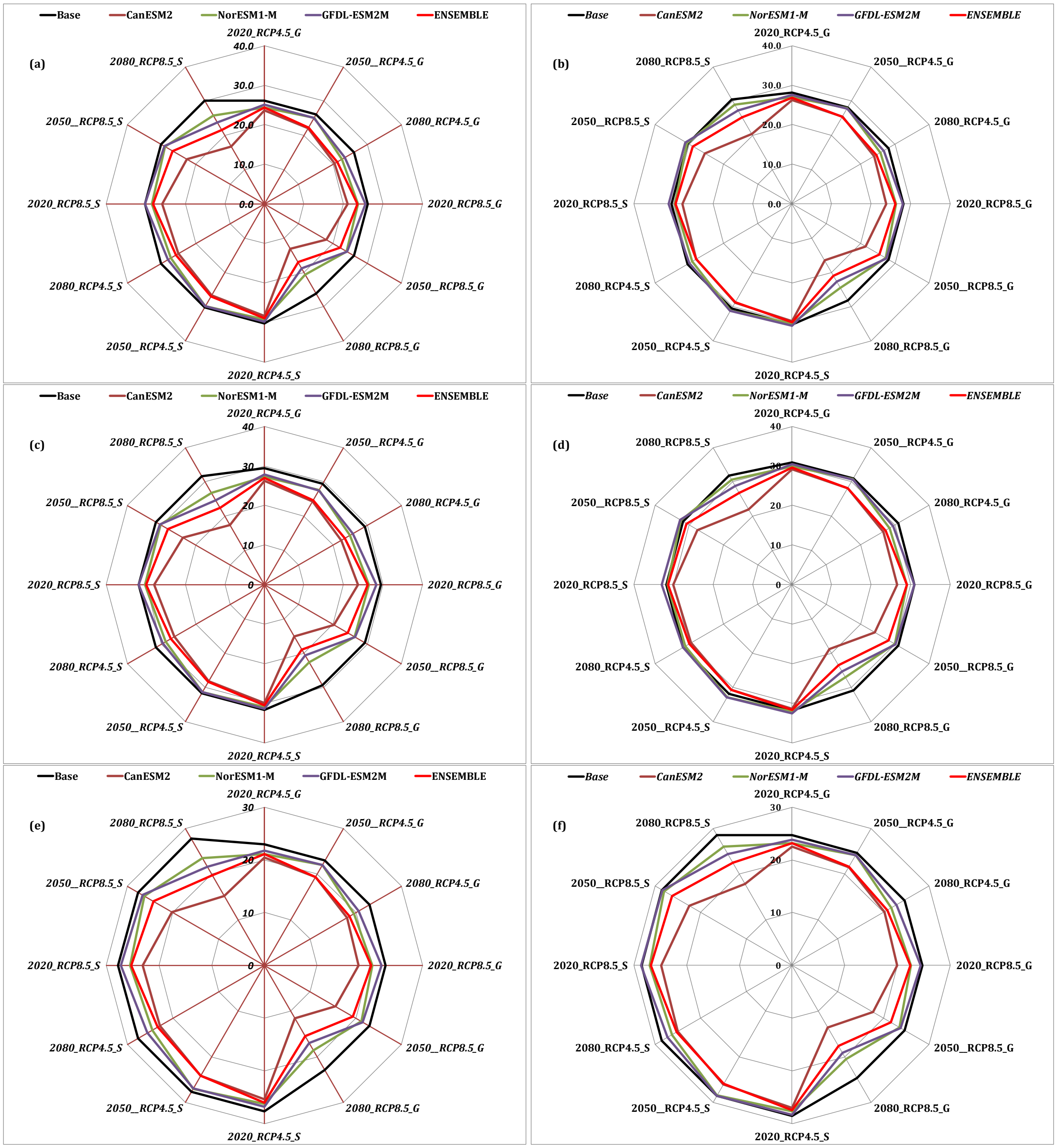

Figure 26: Variability for simulated biomass for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the MAM growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively

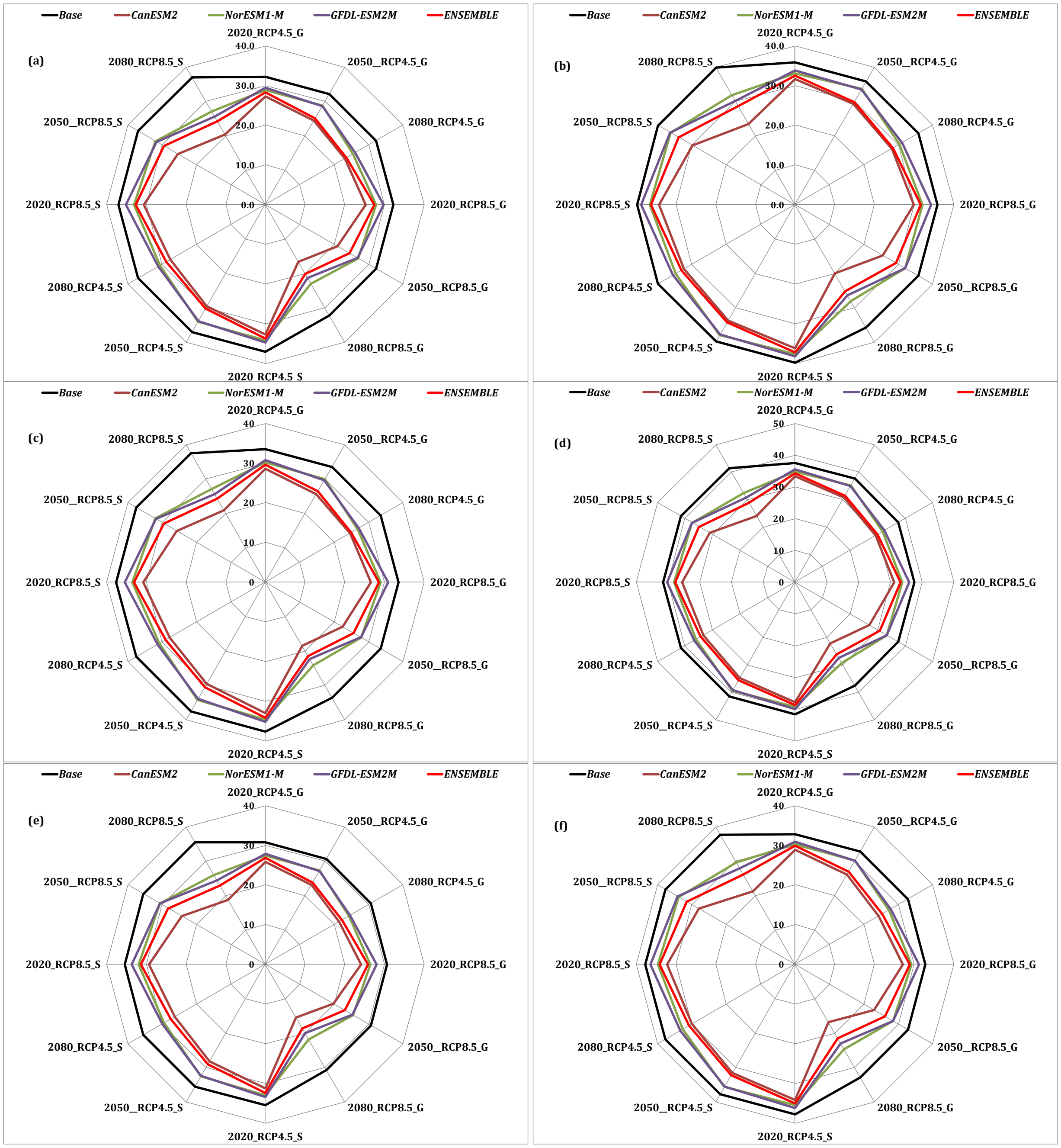

Figure 27: Variability for simulated biomass for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the OND growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively

4.7.4 Effect of Plant Population on Sorghum Grain Yield

Increasing the plant population decreased the grain yield during the MAM season for both varieties across the GCMs (Tables 44 and 45). This could be attributed to additional plants per unit area and the fact that MAM season in the study area is usually unreliable because of its high rainfall variability and the lower amounts of the total rainfall as compared to the OND season. For that reason high plant population will increase the competition for water and the available nutrients. However, decreasing the plant population resulted in an increase in grain yield across the GCMs for both cultivars (Tables 44 and 45). The percentage change in grain yield was relatively higher with the application of inorganic fertilizer compared to the control (0 kg N/ha). The increase in grain yield at low populations for both cultivars might be attributed to availability of more growth resources (light, nutrients and water) for fairly less number of plants thus less competition in utilization of growth resources.

However, during the OND season an opposite scenario was noted across the cultivars. Increased grain yield was noted for both varieties with increased plant population (asymptotic relationship). The attribution is the season is less variable and always receives high amounts of rainfall such that there is enough moisture and that the competition for water and the available nutrients for the higher number of plants is less. Hence, the highest plant population recorded an increase in grain yield while the low plant population recorded a decrease in grain yield. The percentage change in grain yield in all the GCMs for both cultivars tended to increase with fertilizer application compared to the control (0 kg N/ha). Similar results were reported by Zand *et al*., (2014); Getachew (2014); Shapira and Wortmann 2006.

The observed increase in grain yield of sorghum with a decrease in plant population during the MAM growing season, indicates the ability of sorghum to adjust final grain yield through compensatory growth (early flowering and early maturity) as compared to the standard practice. However, the yield compensatory mechanisms observed at lower plant populations were incapable of equilibrating sorghum grain yield to that obtained from the highest plant population during the OND season. This could be because the advantages brought about by the yield compensation mechanisms were offset by the reduced number of panicles per unit area in the lower population.

This shows that while significant reductions occurred in the sorghum grain yield in the highest plant population during MAM season because of variation of the seasonal rainfall characteristics, it is the number of panicles that essentially contribute to higher grain yield in closely planted sorghum.

At both increased and reduced plant populations, the variability of the sorghum yield for the two cultivars was higher for the base period than in a changed climate during both growing seasons (Figures 28 and 29). For both seasons the variations in the yield increased with increase in plant population and decreased with decrease in plant population. During both MAM and OND seasons the variability of the grain yield increased with fertilizer application regardless of the plant population considered. It was also observed that the variability of the yield for Gadam cultivar was lower than that of the Seredo cultivar under both climates and plant populations.

Table 44: Percentage mean changes on grain yield at 0N and 50N fertilizer application rates between population of 66,666 plants ha-1 and two different plant populations 53,333 plants ha-1 and 88,888 plants ha-1 for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the Gadam cultivar during the MAM and OND growing seasons

N-levels ($kgha^{-1}$)	**CORDEX Models**	**88,888 plants ha^{-1}**						**53,333 plants ha^{-1}**					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**Present**	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	2.6	2.6	2.6	2.6	2.6	2.6
	CanESM2	-3.5	-3.4	-2.8	-0.4	-1.2	-1.9	1.0	0.0	0.3	3.3	1.8	1.2
	NorESMI-M	-5.5	-4.4	-2.7	-3.9	-3.4	-2.1	1.2	0.2	0.4	1.0	0.4	0.5
	GFDL-ESM2M	-5.3	-3.4	-3.5	-4.9	-3.1	-2.5	1.7	0.9	0.5	1.1	0.8	0.2
	Ensemble	-5.4	-3.9	-3.5	-4.3	-2.8	-1.4	0.1	0.2	0.0	0.5	0.3	0.8
50N (MAM)	**Present**	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	2.0	2.0	2.0	2.0	2.0	2.0
	CanESM2	-2.1	-0.7	-0.9	-2.9	-5.6	-6.3	0.4	1.5	1.3	1.8	0.4	1.0
	NorESMI-M	-4.4	-1.3	-1.1	-1.2	-0.3	-2.5	0.1	1.8	0.3	2.1	1.5	0.6
	GFDL-ESM2M	-4.1	-0.8	-1.1	-3.4	-0.2	-2.5	0.3	0.7	1.0	0.3	1.4	0.9
	Ensemble	-3.1	-1.9	-0.4	-1.4	-1.3	-3.8	0.9	0.2	1.7	1.5	1.3	0.4
0N (OND)	**Present**	4.9	4.9	4.9	4.9	4.9	4.9	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
	CanESM2	2.8	2.7	1.9	2.1	1.5	2.1	-6.9	-7.2	-5.9	-6.4	-4.9	-4.7
	NorESMI-M	2.4	2.4	2.3	2.4	2.7	2.1	-7.0	-7.2	-6.0	-5.1	-6.6	-4.5
	GFDL-ESM2M	2.2	2.2	2.3	2.3	2.6	2.4	-6.9	-6.4	-6.1	-5.4	-6.0	-4.3
	Ensemble	2.1	2.4	2.1	1.8	1.6	2.4	-6.9	-7.1	-6.6	-5.9	-5.9	-4.0
50N (OND)	**Present**	7.5	7.5	7.5	7.5	7.5	7.5	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0
	CanESM2	8.6	8.9	8.5	9.1	8.4	7.3	-10.9	-10.9	-11.3	-11.7	-10.8	-12.7
	NorESMI-M	8.2	8.4	8.5	9.4	9.3	8.4	-10.3	-10.6	-10.2	-10.8	-10.9	-11.6
	GFDL-ESM2M	8.2	8.1	7.2	9.2	9.3	8.0	-10.4	-10.2	-11.5	-10.7	-10.8	-11.4
	Ensemble	8.3	8.6	8.9	9.1	8.4	7.5	-10.3	-10.5	-10.9	-11.2	-11.0	-11.4

Table 45: Percentage mean changes on grain yield at 0N and 50N fertilizer application rates between population of 66,666 plants ha-1 and two different plant populations 53,333 plants ha-1 and 88,888 plants ha-1 for three future periods for the CORDEX models and two Representative Concentration Pathways (RCPs): 4.5 and 8.5 for the Seredo cultivar during the MAM and OND growing seasons

N-levels (kgha^{-1})	CORDEX Models	88,888 plants ha^{-1}						53,333 plants ha^{-1}					
		2010-2039		**2040-2069**		**2070-2099**		**2010-2039**		**2040-2069**		**2070-2099**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0N (MAM)	**Present**	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	7.4	7.4	7.4	7.4	7.4	7.4
	CanESM2	-3.4	-2.6	-3.3	-2.4	-2.3	-2.8	5.5	4.2	2.1	1.5	2.3	0.0
	NorESMI-M	-7.0	-2.1	-2.1	-3.4	-4.6	-2.4	3.6	7.6	5.1	3.3	3.7	1.8
	GFDL-ESM2M	-6.4	-2.4	-5.0	-3.2	-3.8	-2.3	3.5	7.2	4.5	3.2	3.7	1.6
	Ensemble	-4.6	-3.3	-4.6	-3.2	-3.5	-2.4	5.6	5.7	4.2	2.8	2.5	1.6
50N (MAM)	**Present**	-9.6	-9.6	-9.6	-9.6	-9.6	-9.6	6.9	6.9	6.9	6.9	6.9	6.9
	CanESM2	-3.6	-2.6	-2.9	-0.9	-1.9	0.2	5.3	3.0	2.0	-0.1	1.0	-3.2
	NorESMI-M	-7.7	-3.5	-3.1	-3.5	-4.7	-0.6	3.8	6.6	3.8	2.4	2.8	-0.1
	GFDL-ESM2M	-7.0	-6.5	-2.8	-2.7	-3.3	-0.4	3.7	3.7	4.4	1.9	2.8	-0.5
	Ensemble	-7.2	-3.9	-4.4	-2.8	-2.8	-0.3	4.0	5.4	3.5	1.7	1.3	-0.7
0N (OND)	**Present**	3.3	3.3	3.3	3.3	3.3	3.3	-5.7	-5.7	-5.7	-5.7	-5.7	-5.7
	CanESM2	2.1	3.6	1.6	1.4	0.9	-0.3	-5.9	-5.7	-5.8	-6.1	-5.1	-5.1
	NorESMI-M	3.6	2.9	1.7	1.3	2.0	0.4	-5.6	-5.4	-6.0	-5.6	-6.1	-5.2
	GFDL-ESM2M	2.8	2.3	1.7	1.0	1.3	0.2	-5.8	-5.8	-5.9	-5.5	-5.8	-4.7
	Ensemble	2.5	2.8	2.0	1.2	1.3	0.2	-5.7	-5.3	-5.9	-5.5	-5.5	-4.5
50N (OND)	**Present**	4.9	4.9	4.9	4.9	4.9	4.9	-7.1	-7.1	-7.1	-7.1	-7.1	-7.1
	CanESM2	6.9	8.2	7.1	8.0	7.1	6.9	-8.5	-9.0	-9.5	-9.4	-9.1	-10.4
	NorESMI-M	6.8	7.5	7.4	8.1	7.5	6.7	-8.0	-7.9	-8.2	-8.4	-9.6	-9.4
	GFDL-ESM2M	6.9	7.4	7.5	7.6	7.7	6.1	-8.4	-7.9	-8.4	-8.5	-9.1	-9.4
	Ensemble	6.9	7.3	8.6	7.5	7.8	6.0	-8.1	-8.1	-8.9	-8.9	-8.9	-9.5

Figure 28: Variability for simulated grain yield for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the MAM growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively.

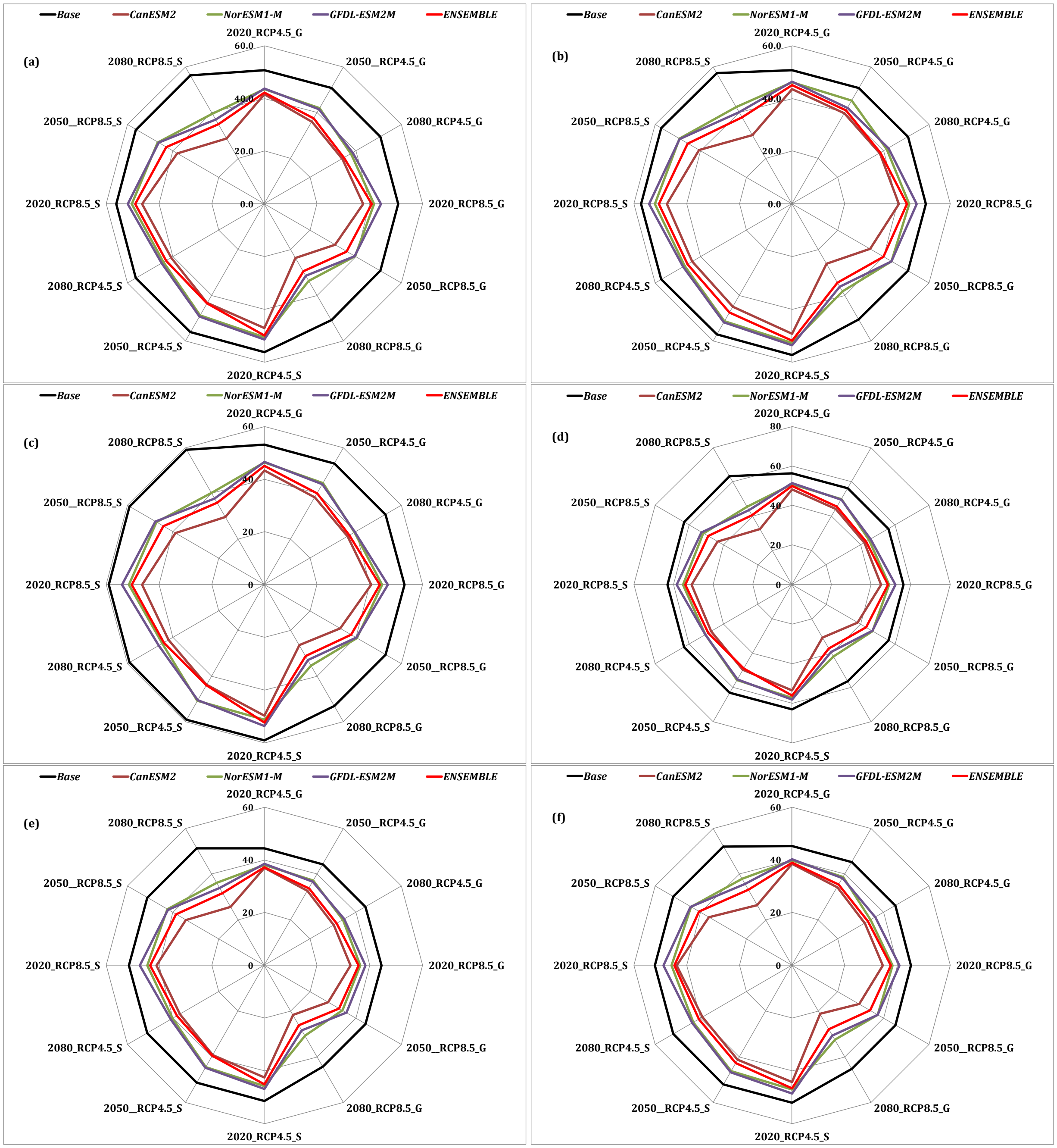

Figure 29: Variability for simulated grain yield for two sorghum cultivars under current (base period) and three future climate scenarios (2020's, 2050's and 2080's) for the CORDEX models and two Representative Concentration Pathways (RCPs) (4.5 and 8.5). G and S represent the Gadam and Seredo cultivars, respectively. Left panel and right panel represent application of 0N and 50N during the OND growing season. (a, b), (c, d) and (e, f) represents 66,666, 88,888 and 53,333 plants ha^{-1}, respectively

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter points out the findings of the study and recommends how these findings can be beneficial to communities, mainly the smallholder farmers in the semi-arid areas of Machakos County. Though these findings were based on case studies carried out in KARLO, Katumani in Machakos County, they can be appropriate to other smallholder farmers with related socio-economic and biophysical conditions all over Kenya.

5.2 Conclusion

High degree of temporal variability linked to both MAM and OND seasons was noted in all the rainfall parameters analyzed except cessation dates. This expresses high level of unpredictability associated with planning of any cropping activity and adds to the threats of farming practice in the study area. In addition, the results of seasonal and annual rainfall amounts showed less stability at all the stations studied. The variability was greater than 40% and 25% for the seasonal and annual rainfall, respectively. From the study the short rainfall season receives more rainfall and tends to be the most reliable than the long rainfall season. For that reason, the growing period during the short rainfall season is more significant for any activities related to agriculture in the study area. Temperature depicted less variation both at seasonal and annual scale (< 5%). Higher variability (45%) in sorghum yield was also noted which translates to increased risks to farmers.

Observed trends depicted statistically non-significant trends in the intra-seasonal rainfall characteristics. The decreasing trends of onset dates indicate a backward shift in the onset of seasonal rainfall resulting to backward shift in land preparation and planting of majority of crops. This makes farmers to experience uncertainties in their planting activity. The average onset dates were 26th March and 1st November for the long and short rainfall seasons, respectively. Crop failure owing to early planting is more or less equal as the possibility of total crop failure due to an early cessation of seasonal rainfall, since the duration of the season is highly correlated with rainfall onset for both rainfall seasons. On the other hand, seasonal and annual rainfall totals in most of stations studied showed decreasing trends. However, statistically significant trends were noted at Iveti and at Machakos DO stations. Low levels of rainfall in combination with declining condition of the soils' would certainly have adverse impacts on crop production. Both maximum and minimum temperature depicted an upward trend at seasonal and annual scales. Such warming trends of temperature are expected to result in quick accumulation of heat units, which sequentially enhances growth and development of sorghum by reducing the number of days for sorghum to reach physiological maturity provided that other vital factors are not limiting. Trend in yield indicate that sorghum yield have not changed considerably during the period 1982 to 2012, for Machakos County, Kenya. Though the trend was increasing it was statistically insignificant.

Results of correlation coefficient indicated that thirteen (13) climatic parameters were found to have contributed significantly during the four stages of growth of sorghum. These parameters were further subjected to step-wise regression analysis so as to identify the climate variables that are critical to the yield of sorghum and their degree of influence on the final yield. Four (4) out of the thirteen (13) observed climatic parameters considered contributed significantly to the variation in the yield of sorghum in Machakos County. These included: total rainfall during the MAM season, minimum temperature for the vegetative phase during the OND season, duration and number of rainy days during the OND season. These four parameters jointly accounted for 90.5% of the total variance in the yield of sorghum in Machakos County.

The effect of different nitrogen and phosphorus application rates was observed on the phenological parameters, growth parameters and yield. The phenological parameters studied in this research were the days to 50% flowering and physiological maturity. The analysis of variance on these parameters indicated that the effect of different treatments was insignificant on phenological parameters. Both days to 50% flowering and physiological maturity in majority of the experiments was also influenced by cultivar effect, but the interactive effects of cultivar, N and P in the four experiments was non-significant. Gadam cultivar took around twelve (12) and seven days (7) earlier than the Seredo in flowering and maturity, respectively. Thus because of high variability in the seasonal rainfall (> 40%) experienced in the study area, farmers are encouraged to plant Gadam rather than Seredo. Above ground biomass weight was not influenced by the different nitrogen and phosphorus application rates except for Experiment 2. It was also not influenced by the interaction effect (nitrogen, phosphorus and cultivar). Regarding to the effect of cultivar on biomass, Seredo produced a higher average biomass (37.5 %) than Gadam in all the four experiments. Sorghum grain yield among various fertilizer application rates was related to general conditions of the soil and their photosynthetic activity. The sorghum plants responded more to N inorganic fertilizer. Presence of high amounts of soil P in the soil restricted the efficient use of P inorganic fertilizer by the plants. The interactive effect (nitrogen and phosphorus) was not significant on grain yield. While the cultivars were dissimilar, they responded uniformly to the application of N and P fertilizer. Seredo cultivar nonetheless, responded quickly to inorganic fertilizer because it produces higher biomass (27.3%) and grain yield (17.1%) than Gadam.

The APSIM-Sorghum model (version 7.8) was effectively calibrated and evaluated for semi-arid eastern Kenya. The predicted phenological development of sorghum by the APSIM model was plausible for the two cultivars. The RMSE between the observed and simulated days to 50% flowering during MAM (OND) was 1.2 (1) and 1.6 (1.3) days, in days to physiological maturity 2.4 (1.0) and 2.9 (1.2) days, in above ground biomass 347.6 (369.6) and 360.7 (427.7) kgha^{-1} and in grain yield 52.3 (155.9) and 227.7 (196.3) kgha^{-1} for cultivar Gadam and Seredo, respectively.

The simulated grain yield of sorghum corresponded well with the observed sorghum grain yield with an overall modified index of agreement of 0.60 and 0.65 for Gadam and Seredo cultivars, respectively. The simulated sorghum grain yield was also noted to be linearly related to the observed sorghum grain yield ($r^2 = 0.76$ and 0.84 for Gadam and Seredo cultivars, respectively).

Regarding the performance of CORDEX GCMs in simulating the climate variables over the study area, both the GCMs and the ensemble showed weaker values of RMSE in simulating rainfall as compared to maximum and minimum temperature and solar radiation. The weaker values of RMSE for rainfall are an indication of low agreement between the models and observed data. Thus there is need to bias correct the data. The modified index of agreement values ranged from 0.19 to 0.54 across the climate variables and seasons. The values close to one (1) are considered as better simulations. Based on overall performance of the models in simulating the three climate parameters, the ensemble, CanESM2, GFDL-ESM2M, NorESM1-

M, MIROC5, MPI-ESM-LR, EC-EARTH and CNRM-CM5 (in order of decreasing ranking) were able to simulate the observed climate variables in the desired period for the study region.

The calibrated and validated APSIM-sorghum model was used to simulate climate change impacts on sorghum growth and development in semi-arid eastern Kenya, using climate projections data of three CORDEX GCMs and the ensemble and considering RCP 4.5 and RCP 8.5. Projected mean changes on days to 50% flowering showed a consistent decline for both sorghum varieties during both the long and short growing season with the application of different rates of fertilizer. During MAM and OND growing seasons, the days to reach 50% flowering for both short and long season sorghum cultivars was reduced by 21.5% and 15.3% and 25.0% and 19.8% for RCP4.5 and RCP8.5, respectively. During MAM and OND growing seasons, the days to maturity for both short and long season sorghum cultivars was reduced by 16.2% and 12.3% and 21.2% and 16.3% for RCP4.5 and RCP8.5, respectively. Hence Gadam provides the best option in terms of cultivar choice because under the changed climate its phenological dates were shorter compared to Seredo.

The decline on days to 50% flowering and physiological maturity was relatively higher during the MAM season as compared to the OND season. All models indicate that under both RCPs, the approach to the end century (2080's) showed a greater decline in the number of days to reach 50% flowering and physiological maturity when assessed against the current climate (baseline). Under both current and changed climate, the long season variety, Seredo, gives higher above ground biomass than the short season variety Gadam. There was slight increase or decrease in biomass for both varieties under climate change. The average mean yields for Gadam under both current and changed climate during the two growing seasons was higher than for Seredo. It has been noted that under changing climate sorghum grain yields will constantly increase for both cultivars over the three time slices with up to 85.3% increase in the end of the century (2070-2099). The magnitude of change in the yield was higher for Seredo than for Gadam. From the study it can be deduced that the sorghum grain yield showed greater variability as compared to the other variables (days to 50% flowering, days to physiological maturity and total above ground biomass). The GFDL-ESM2M and CanESM2 models projected lowest and highest increase in both mean temperatures and rainfall and this was replicated in the outputs of APSIM model particularly for days to 50% flowering, days to physiological maturity, biomass and sorghum grain yield.

Quantification of the impacts and adaptation using crop models permits understanding of how changes in temperature and rainfall affect crop productivity and provide the momentum to push for suitable agronomic management options to curb the impacts of climate change on agricultural productivity and maximize yields thus reducing further food insecurity. The agronomic management options assessed in this study were variation in the planting population.

Increasing the plant population (88,888 plants ha^{-1}) resulted to delayed days to 50% flowering and physiological maturity for both cultivars under both the present and changed climate as compared to the standard practice (66,666 plants ha^{-1}) due to increased plant competition for the available growth resources (soil moisture, soil nutrients, and light) resulting to an extended vegetative growth period. On the other hand, early flowering and maturity was noted with reduced plant population (53,333 plants ha^{-1}) as compared to the standard practice, mainly due to comfortable growth as result of sufficient growth resources. Across the cultivars, the number of days to 50% flowering and attainment of physiological maturity was less variable (less than 20%) for both plant populations during both MAM and OND growing seasons under both the base period and changed climate. Above ground biomass weight for both cultivars and across the GCMs was found to increase and decrease for the highest and lowest plant population, respectively. The percentage change in the total above ground biomass was relatively higher during short rainfall season as compared to the long rainfall season. The baseline period showed greater variations in biomass yield as compared to the changed climate for the two cultivars studied. The variations of biomass increased with increase in plant population and decreased with decrease in plant population. Highest (lowest) and lowest (highest) values of grain yield were recorded from highest and lowest plant populations, respectively during the OND (MAM) growing season. This could be attributed to additional plants per unit area and the fact that MAM season in the study area is usually unreliable because of its high rainfall variability and the lower amounts of the total rainfall as compared to the OND season thus high plant population will increase the competition for water and the available nutrients. At both increased and reduced plant populations, the variability of the sorghum yield for the two cultivars was higher for the base period than in a changed climate during both growing seasons. For both seasons the variations in the yield increased with increase in plant population and decreased with decrease in plant population. From these conclusions farmers should plant the Gadam cultivar currently and in the changed climate with the highest plant population (88,888 plants ha^{-1}) during the OND growing season. Conversely, they should plant Seredo cultivar with the lowest plant population (53,333 plants ha^{-1}) during the MAM growing season.

5.3 Recommendations

Because of high temporal variability of the intra-seasonal rainfall characteristics, the government should invest greatly in early warning systems so as to aid smallholder farmers in the county in planning or adjusting their farm operations. Likewise, effective communication of climate information and services is important for adaptation by households because communication enhances understanding and awareness. On this matter, suitable communication channels such as the use of local radio stations broadcasting in local language may be utilized to guarantee that such climate information and early warnings get to the anticipated farmers. In addition, based on level of awareness and access to supplementary irrigation, farmers could complement crops by irrigation during episodes of deficit rain.

Due to warming trends , delayed onset and little possibility of irrigating crops, growing and breeding of rapidly maturing sorghum varieties or other cereal crops that are tolerant to heat stress and drought may also help in cushioning farmers from impacts of climate change such as complete crop failure. For a long term solution, government, policy makers and donors should build up/support irrigation amenities and water harvesting skills (digging water pans and sand dams) under variable and changing climate.

Future studies should consider carrying out similar research on multi-locations in the ASALs of Kenya, where climate change is already restricting agricultural productivity, so as to advance validity of results obtained in this research

Efficient use of fertilizer could be enhanced by using techniques such as precision agriculture and micro-dosing. Effective implementation of this can be achieved by having on-farm demonstration trials in the study area. This could be funded by seed companies and agro-chemical companies within the country. In addition the effect of fertilizer application rates on seed quality of sorghum should be incorporated in future studies to acquire satisfactory evidence not only on the phenological parameters, growth parameters and yield, but also the seed quality.

Though average yields of the long season sorghum cultivar are higher under both current and future climate, agricultural extension officers should promote and encourage smallholder farmers to grow short season variety as they show lesser inter-seasonal yield variability than the late maturing variety and because of high variability in the duration of seasonal rainfall. The government also needs to develop policies that guarantee availability and accessibility to sufficient amounts of seed of appropriate sorghum varieties for smallholder farmers.

Since crop farming is more susceptible to variable rainfall in comparison to livestock production, in future, farmers in the region may as well invest more in livestock. Instead of depending principally on crop farming, as they presently do, smallholder farmers need to utilize and/or reinforce other forms of livelihoods within and outside agriculture as climate changes so as to act in response to an array of probable future climates including unexpected climate shocks.

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