ASSESSING IMPACT OF CLIMATE CHANGE ON SORGHUM (*Sorghum bicolor L.)* AND WHEAT *(Triticum aestivum L.)* PRODUCTION IN NORTHERN ETHIOPIA

MSc THESIS

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APPROVAL SHEET

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We hereby certify that we have read and evaluated this thesis entitled: **Assessing Impact of Climate Change on Sorghum and Wheat Production in Northern Ethiopia** prepared under our guidance by Eshetu Zewdu Tegegne. We recommend that it be submitted as fulfilling the thesis requirement.

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As member of the Board of Examiners of the Final MSc Thesis Open Defense Examination**,** we certify that we have read and evaluated the Thesis prepared by **Eshetu Zewdu Tegegne** and examined the candidate. We recommend that the thesis be accepted as fulfilling the Thesis requirements for the Degree of Master in Agro-meteorology and Natural Risk Management.

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DEDICATION

This thesis is dedicated to my beloved brother Demelash Zewdu and for all families and friends for their moral support and encouragement during my stay at Haramaya University.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this thesis. Any scholarly matter that is included in the thesis has been given recognition through citation.

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BIOGRAPHICAL SKETCH

The author, Eshetu Zewdu, was born on 11 January 1988 in Ambasel Woreda, South Wollo Zone of Amhara National Regional State, from his father Zewdu Tegegne and his mother Beletu Molla. He attended his elementary education at Golbo Elementary School and Secondary and Preparatory education at Gerado Secondary School and Dessie Memhir Akalewold Preparatory School. After a successful accomplishment of Ethiopian National School Leaving Certificate Examination, he joined Arba Minch University and graduated with BSc degree in Meteorology Science in July, 2009.

After graduation, he was employed by the National Meteorology Agency of Ethiopia (NMA) and assigned to work as an Early Warning and Forecast Analysis Expert in Semera Meteorological Branch Directorate from October 2009 to February 2012. In March 2009 he left NMA and joined Ethiopian Institutes of Agricultural Research where he served until he left in September 2014 to pursue Post Graduate (MSc) program at Haramaya University in Agro-Meteorology and Natural Risk Management.

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ACRONYMS AND ABBREVIATION

AgMIP	Agricultural Model Inter-compression and Improvement Project
AOGCM	Coupled Atmosphere-Ocean General Circulation Models
CC	Climate Change
CCA	Climate Change Adaptation
CERES	Crop Environment Resource Synthesis
CIMIP5	Coupled Inter-Comparison Project phase five
CIMMYT	International Maize and Wheat Improvement Center
CSM	Crop Simulation Modeling
CV	Coefficient of Variation
DSSAT	Decision Support Tool for Agro technology Transfer
EIAR	Ethiopian Institutes of Agricultural Research
FAO	Food and Agriculture Organization
GCM	Global Climate Model
GLSAT	Global Land Surface Air Temperature
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
JJAS	June July August September
MAE	Mean Absolute Error
MARC	Melkassa Agricultural Research Centre
MME	Multi Model Ensemble
MRARC	Mekele Regional Agricultural Research Center
NCEP	National Center for Environmental Protection
NMA	National Meteorology Agency
QC	Quality Control
RCPs	Representative Concentration Pathways
RMSE	Root Mean Square Error
RUFORUM	Regional Universities Forum for Capacity Building in Agriculture
TAR	Third Assessment Report
UNEP	United Nation Environmental Program
UNFCCC	United Nation Framework Convention on Climate Change

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ABSTRACT

Agriculture is the most vulnerable sector to the impacts of climate change and climate variability and needs high demand for quantitative information on the impacts. In this case, a crop model, Decision Support System for Agro-technology Transfer, and global climate models were used to assess climate impacts on sorghum and wheat yields and to explore specific adaptation options for mid (2040-2069) and end (2070-2099) centuries under medium (RCP4.5) and highest (RCP8.5) emission scenarios in northern Ethiopia. The crop simulation model was calibrated and validated using crop experimental, soil and historical climate data sets from Enderta and Kobo sites. With this, the simulation experiment was carried out for early maturing sorghum cultivars (Teshale and Melkam) and Mekele-1 wheat cultivar using historical climate data of Sirinka (1985-2014), Kobo (1985-2014) and Enderta. (1981-2010) and future climate change scenario data downscaled from general circulation models. The simulation result revealed that sorghum yield is expected to decrease by 1.2-23% conditional to emission scenarios, period of analysis, variety and the study location considered. Whereas, wheat yield is expected to increase by 2.2-6.6% depending on the emission scenarios considered by 2050s while yield is predicted to decline by 2.3% at the end of the century under the highest emission scenarios. Result of thesensetivity analysis indicated that Teshale variety is highly sensitive to environmental change from the baseline climate at Kobo and Sirinka. On the other hand, regardless of rainfall variation, a rise in temperature up to 3 °C would result in an increase in yield by 2.3-13.8% for melkam variety. However, the rise of atmospheric CO_2 *by 540 and 750 ppm from the current level would result in an increase of yield from 4.5 to 6.9% for sorghum and up to 25.7% for wheat. However, adaptation practices such as, increasing fertilization and increasing plant population would offset the adverse impacts of climate change on sorghum and wheat production. Mid-June planting for sorghum production at Sirinka and Kobo gives better yield than normal and late planning; while mid-June and mid-July planting would intensify the negative impactsof climate change at Enderta. All in all, change in planting date at Enderta would not reward wheat production under the changing climate.*

Key words: Adaptation, Climate change, Impact, Sensitivity, Sorghum, Wheat

1. INTRODUCTION

1.1. Background of the study

Climate change has been described as the most significant environmental threat of the 21st century and its potential long-term impact on crop production is a topical issue worldwide. This is partly because the potential impacts of climate change (CC) on agriculture is highly uncertain and potentially impact on weather and soil which are the two important factors for crop production (IPCC, 2014; UNEP, 2008; World Bank, 2006, UNFCC, 2007)

The negative impacts of climate change are likely to be most serious in the tropics and subtropics, where the majority of developing countries are located and where the capacity to adapt to changes is most limited; it is widely accepted that developing countries are largely maladapted to future climate risks. The adverse impacts of climate change will fall disproportionately on the most vulnerable in the least developed and developing countries (UNEP, 2008, UNFCCC, 2007).

In most countries where agricultural productivity is already low and the means of coping with adverse events are limited, climate change is expected to reduce productivity to even lower levels and make production more erratic and exerts a significant control on the day to-day economic development, particularly for the agricultural and water-resources sectors, at regional, local and household scales (Deressa, 2008). Long term changes in the patterns of temperature and precipitation, that are part of climate change, are expected to shift production seasons, pest and disease patterns, and modify the set of feasible crops affecting production, prices, incomes and ultimately, livelihoods.

Agricultural production systems of developing countries like Ethiopia are highly characterized by low productivity, smallholder farming system, lack of modern farming technologies and largely rain-fed production and makes highly sensitive to the impacts of climate variability and change. According to the Intergovernmental Panel on Climate Change (IPCC, 2014) developing countries agriculture is severely affected by desertification, floods, drought, rising temperature and extreme.

So adaptation of climate change to agricultural sector for the adverse effects of climate change will be imperative to protect the livelihoods of the poor and to ensure food security.

Adaptation can greatly reduce climate vulnerability of rural communities by making them able to adjust to climate variability and change and helping them to cope with adverse consequences (Adger et al., 2007; Hellmuth, 2007; Bryan et al., 2009; IPCC, 2012).

1.2. Statement of the Problem

Climate change is already impacting agriculture, food security and will make the challenge of ending hunger and malnutrition even more difficult. According to the United Nations (2015) and International Fund for Agricultural Development IFAD (2011), there are still 836 million people in the world living in extreme poverty (less than USD1.25/day) and at least 70 percent of the very poor live in rural areas, most of them depending partly or completely on agriculture for their livelihoods. It is estimated that 500 million smallholder farms in the developing world are supporting almost 2 billion people, and in Asia and sub-Saharan Africa these small farms produce about 80 percent of the food consumed (World Bank, 2007).

Climate change is a global concern and its impact on agriculture in developing countries have been increasing (IPCC 2014) and effort is needed to estimate the impact (Mendelsohn and Tiwari, 2000; IFAD, 2011). At the present growth rate the population is expected to increase to about 129.1 million by the year 2030 (Deressa, 2007).

Ethiopia is among the most vulnerable countries in Africa due to its great reliance on climate sensitive sectors, particularly agriculture (World Bank, 2006; Thornton *et al.*, 2008; Hellmuth, 2007). Historically, strong links have been observed between climate variability and the overall performance of Ethiopia´s economy, reflected by high correlation between rainfall and GDP fluctuations (World Bank, 2006). The changing rainfall pattern in combination with warming trends could make rain-fed agriculture more risky and aggravate food insecurity in Ethiopia. The northern parts of the country, which is highly characterized by low, erratic, and uneven distribution of rainfall and recurrent drought, is seriously affected by the direct and indirect impacts of climate change related impacts. The recent past recurrent droughts occurred in the region is well recognized that poses serious threats to agricultural production and livelihoods of communities (Degefu, 1987; Addis, 2009; Gebrehiwot and Van der Veen, 2011).

So advanced research tools, like crop simulation modeling, are needed to predict (Amanullah *et al*., 2007) and understand the variability and expected future changes of climatic conditions, particularly characteristics of rainfall, temperature and evapotranspiration is crucial for planning and designing appropriate adaptation strategies. For developing and implementing adaptation programs, more detailed information about the impacts of climate change on various components of farming systems such as which crops and varieties are more vulnerable and which management practices are unviable is required. In this case, sorghum and wheat, major staple food crops of the area were selected to assess the possible impacts of future climate on production system of the crops in the respective sites.

Hence, this study is aimed to quantify the current and the projected impacts of climate change on agricultural production systems to make a comprehensive assessment of climate change on crop growth and performance under rain-fed conditions by integrating downscaled climate scenarios with crop simulation models.

Research questions

- What are the possible impacts of climate change (temperature, precipitation, carbon dioxide) on the yields of sorghum and wheat under a given climate change scenario?
- To which climate variable does the crop is most sensitive?
- What kinds of adaptation measures should be suggested to reduce the adverse effects of climate change on wheat and sorghum production system?

1.3. Objective of the Study

The overall objective of the study is to assess the impact of climate change and explore alternative adaptation options for future climates (mid and end century) on *sorghum and wheat* production in northern Ethiopia under different emission scenarios (RCP’s)

1.3.1. Specific objectives

- To assess the impacts of climatic change on *wheat and sorghum* production under different representative concentration pathways (RCPs)
- To test the sensitivity of the model under different climatic variables
- To evaluate the impacts of different adaptation options for sorghum and wheat production in terms of yield for the localities

2. LITERATURE REVIEW

2.1. Global and Regional Climate change

According to the consecutive reports of Intergovernmental Panel on Climate Change (IPCC), evidence of climate change impacts in recent decade is strongest and most comprehensive in natural system. The global average temperature risk is high to very high with global mean temperature increase of 1.5 ^{o}C to 5.4 ^{o}C at the end of the century from the preindustrial level with a widespread impact on global and regional food security and normal human activities, including growing food (IPCC, 2014).

Climate change is a complex biophysical process and is not possible to predict precise future climate conditions but the scientific consensus is that the global land and sea surface temperature continues warming under the influence of greenhouse gases (IPCC, 2014). The fifth assessment report of IPCC also reported increase of global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcing (IPCC, 2013). The observed warming is approximately 0.6°C to 0.7°C over the period. The latest observed global annual average temperature anomaly relative to 1961-1990 climatology from four latest version data sets shows an increasing trend (Fig.1).

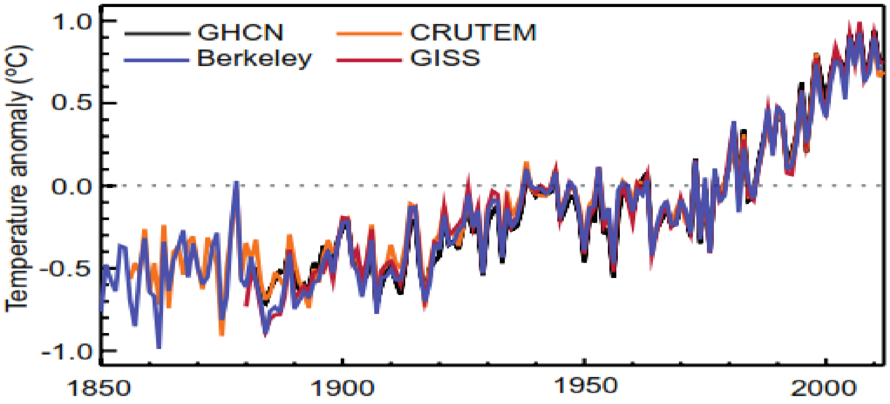


Figure 1. Global annual average land surface air temperature (GLSAT) anomalies relative to 1961 - 1990 climatology from version of data sets (Source: IPCC, 2014)

The Intergovernmental Panel on Climate Change (IPCC) AR5 also predicted the global surface temperature change for the end of 21st century likely to exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, and more likely than not to exceed 2 °C for RCP4.5. Warming will continue beyond

2100 under all RCP scenarios except RCP2.6 and will continue to exhibit inter-annual to decadal variability and will not be regionally uniform (IPCC, 2014).

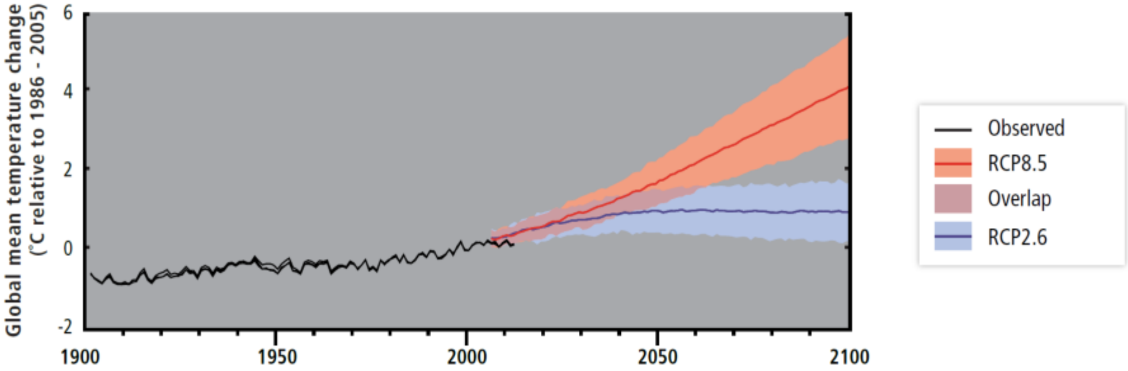


Figure 2. CMIP5 multi-model simulated time series from 1950 to 2100 for (a) change in global annual mean surface temperature relative to 1986–2005 (Source: IPCC, 2014)

Increase of global mean surface temperatures for 2046-2065 and 2081–2100 relative to 1986–2005 is projected likely to be in the ranges of 1.0-2.0 and 1.0-3.7 °C respectively derived from the concentration-driven CMIP5 model simulations (IPCC 2013).

Table 1. Projected change in global mean surface temperature for mid and late 21st century relative to the reference period of 1986-2005

		2046-2065		2081-2100	
Global Mean Surface Temperature Change (°C)	Scenario	Mean	Likely range	Mean	Likely range
	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

(Source: IPCC, 2014)

Since 1960 observed temperature have indicated greater warming rate consistently over the continents. Africa is one already under the stress of climate change and highly vulnerable to climate variability (UNFCC, 2007). The historical climate record for Africa shows warming of approximately 0.7°C over most of the continent during the 20th century and a decrease in rainfall over large portions of the Sahel, and an increase in rainfall in east and central Africa. Future warming across Africa ranging from 0.2°C per decade (low scenario) to more than 0.5°C per decade (high scenario). This warming is greatest over the interior of semi-arid margins of the Sahara and central southern Africa (IPCC, 2007; and IPCC, 2014). The fifth assessment report of IPCC and UNDP reported that the future precipitation projections are more uncertain but likely to increase in eastern Africa and decrease in the southern part (Niang *et al.* 2014).

The tropical forest region of Africa shows a decadal warming rate of 0.29°c and 0.1 °C– 0.3 °C have been observed in South Africa (IPCC, 2013). In South Africa and Ethiopia, minimum temperatures have increased slightly faster than maximum or mean temperatures (Conway *et al.*, 2007).

In all RCPs, atmospheric CO_2 concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of CO_2 to the atmosphere during the 21st century (Table 2).

Table 2: Projected CO_2 emission for the 2012 to 2100 period compatible with the RCP atmospheric concentration simulated by CMIP5 earth system model ((IPCC, 2013)

Scenario	Cumulative CO_2 Emission 2012 to 2100			
	GtC		$GtCO_2$	
	Mean	Range	Mean	Range
RCP2.6	270	140-410	990	510-1505
RCP4.5	780	595-1005	2860	2180-3690
RCP6.0	1060	840-1250	3885	3080-4585
RCP8.5	1685	1415-1910	6180	5185-7005

(Source: IPCC, 2013)

2.2. Impacts of Climate Change on Crop Production

Climate change, agriculture and food security are now a subject of global concern. This is evident from the number of empirical literatures that is currently available on the subject matter. However, most seem to focus on the industrial countries where the economic impacts are likely to be less harmful because of better adaptation techniques and technology than the developing nations (IPCC, 2014).

In many parts of the world, climate change is one of the biggest risk factors impacting on agricultural systems performance and management. Climate change worsens the living conditions for many who are already vulnerable, particularly in developing countries because of the lack of assets and adequate insurance coverage. Climate change is projected to overall decrease in the yields of cereal crop in Africa through shortening growing season length, amplifying water stress and increasing incidence of diseases, pests and weeds outbreaks (Niang et al., 2014).

Among the various environmental changes brought by climate change that limits crop yields, heat and water stresses are considered the most important (Prasad et al. 2008). The major impacts of climate change are predicted to be harsh in sub-Sahara Africa because of the region's characteristic of high heat stress and low precipitation (world Bank, 2006; IFPRI, 2007; Thornton *et al*, 2008).

According to the most recent IPCC report, changes in climates over the last 30 years have already reduced global agricultural production in the range 1-5 % per decade particularly for tropical cereal crops such as maize and rice and evidence of climate change impacts is strongest and most comprehensive for natural systems (IPCC, 2014).

In most countries where agricultural productivity is already low and the means of coping with adverse events are limited, climate change is expected to reduce productivity to even lower levels and make production more erratic.

Africa is most vulnerable to climate change and climate variability and the situation is aggravated by the interaction of multiple stresses occurring at various levels and low adaptive capacity. Agricultural production and food security (including access to food) in many African countries and regions are likely to be severely compromised by climate change and climate variability (IPCC, 2014). A number of countries in Africa already face semi-arid conditions that make agriculture challenging, and climate change will be likely to reduce the length of growing season as well as force large regions of marginal agriculture out of production. Projected reductions in yield in some countries could be as much as 50% by 2020, and crop net revenues could fall by as much as 90% by 2100, with small-scale farmers being the most affected. This would adversely affect food security in the continent (IPCC, 2014).

Projected impacts of climate change negatively affects, with no adaptation, major crops (wheat, rice, and maize) in tropical and temperate regions for local temperature increases of 2°C or more above late 20th century levels but the projected impacts vary across crops and regions and adaptation scenarios (IPCC, 2013). But climate change will have significant impacts on agriculture, particularly in East Africa where there is variation in topography and climate. Climate variability adds a time dimension to environmental heterogeneity. According to IFPRI (2007), negative yield impacts are projected to be largest for wheat, whereas overall yields for millet and sorghum are projected to be slightly higher under the changed climate.

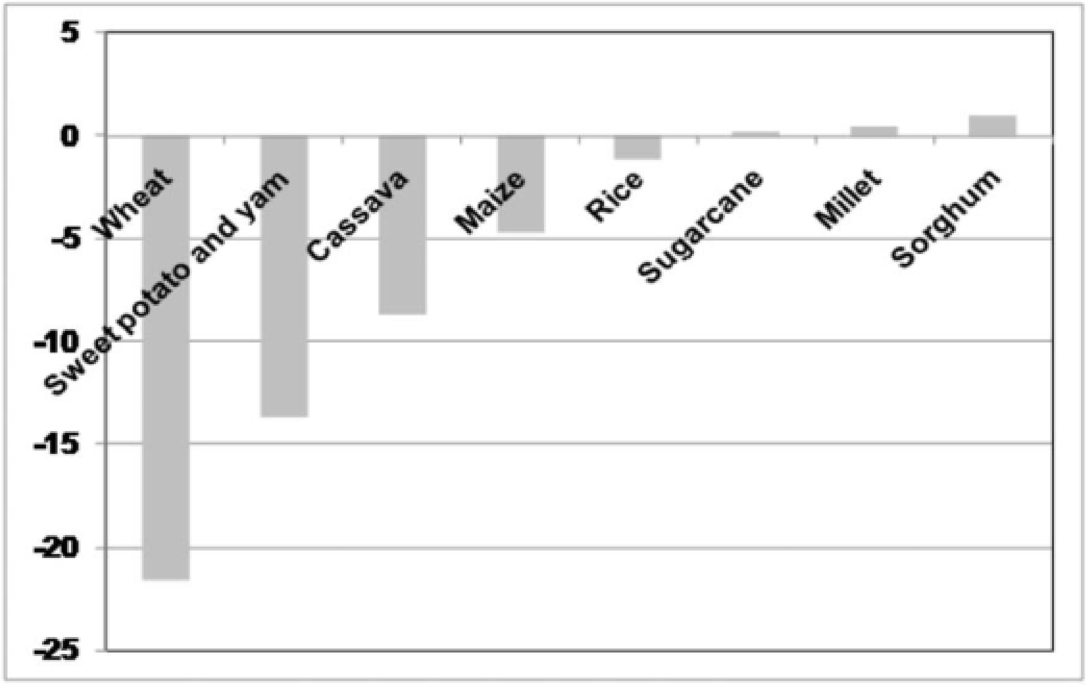
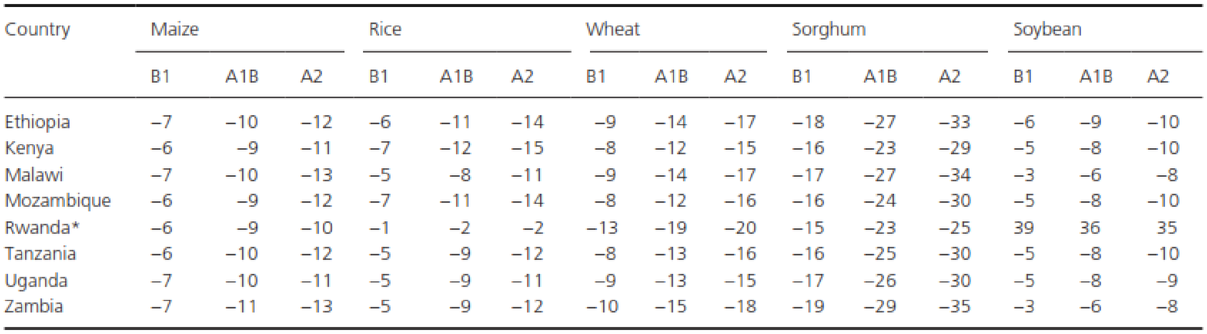


Figure 3. Yield change (%) by crop as a result of climate change by 2050 for SSA (IFPRI, 2007)

The impact of climate change on crop yields in eastern Africa region is largely negative. Among the grain crops, wheat is reported as the most vulnerable crop, for which up to 72% of the current yield is projected to decline. However, millet and sorghum, are more resilient to climate change for which projected impacts on crop yields are <20%.

Table 3. Projected percent change in yield under three climate change scenarios (B1, A1B, and A2) by 2080s



Country	Maize			Rice			Wheat			Sorghum			Soybean		
	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2
Ethiopia	−7	−10	−12	−6	−11	−14	−9	−14	−17	−18	−27	−33	−6	−9	−10
Kenya	−6	−9	−11	−7	−12	−15	−8	−12	−15	−16	−23	−29	−5	−8	−10
Malawi	−7	−10	−13	−5	−8	−11	−9	−14	−17	−17	−27	−34	−3	−6	−8
Mozambique	−6	−9	−12	−7	−11	−14	−8	−12	−16	−16	−24	−30	−5	−8	−10
Rwanda*	−6	−9	−10	−1	−2	−2	−13	−19	−20	−15	−23	−25	39	36	35
Tanzania	−6	−10	−12	−5	−9	−12	−8	−13	−16	−16	−25	−30	−5	−8	−10
Uganda	−7	−10	−11	−5	−9	−11	−9	−13	−15	−17	−26	−30	−5	−8	−9
Zambia	−7	−11	−13	−5	−9	−12	−10	−15	−18	−19	−29	−35	−3	−6	−8

(Source: Climate change and eastern Africa: a review of impact on major crops, 2015)

2.2.1. Wheat

Wheat is a cool season crop and increasing temperature shortens its growth period by accelerating phenological developments, resulting in reduced yield (You *et al*., 2005; Asseng *et al.*, 2011). Studies suggested that a 1°C increase in temperature above optimum (15-20^{o}C) reduces wheat yield by 10% (Brown, 2009) and studies confirmed that wheat is negatively affected by future projected climate compared to other crops in East Africa (Liu et al. 2008). Compared to sorghum wheat has a lower optimum temperature (Liu *et al*., 2008). According to Lobell and Field (2007) a 4°C rise in temperature will result in a 15% decrease in wheat production in low latitudes and east Africa experienced 10–13%, 16–20%, and 17–24% wheat yield decrease by the end of the 21st century under B1, A1B and A2 storylines, respectively.

2.2.2. Sorghum

In terms of quantity, sorghum is the second most important crop in Africa after maize and is the most important crop in the semiarid tropics (Obalum *et al*., 2011). According to Liu *et al*. (2008) optimum vegetative growth temperature of sorghum is 26–34°C and an optimum reproductive growth temperature is 25–28°C. Currently, most of the sorghum in Sub-Saharan Africa (SSA) region is grown under sub-optimum temperatures. Knox et al. (2012) reported only a 15% sorghum yield reduction in the African continent by the 2050s. Most other simulation studies that focused on SSA or East Africa predict small changes in future sorghum production in East Africa. Liu *et a*l. (2008) also simulated sorghum yield in SSA and Lobell *et al*. (2008) simulated sorghum production in East Africa and both projected only small changes in sorghum production by 2030s compared to the 1990s and 2000s.

2.2.3. Climate Change and crop production in Ethiopia

Agriculture, which is the mainstay of Ethiopian economy is highly exposed for the impacts of climate change which threats to sustained economic growth that will lead to extended poverty. However, like the rest of Sub-Saharan Africa, Ethiopia's agriculture is mainly rain-fed and therefore highly vulnerable to climate change. Rain-fed crop production is the basis of all subsistence farming in most parts of Ethiopia and accounts for more than 95% of the land area cultivated annually. In general farming is mixed: both animal and crop production is important. A typical farming household in the semi-arid areas owns just a small portion of land (generally less than one hectare) on which crops are produced and which also partly supports variable numbers of cattle, goats, donkeys, and sheep (Deressa., 2007). According to Deressa (2007) climate change, especially increasing temperature has a damaging impact on Ethiopian agriculture.

In Ethiopia, models indicate that the average daily rainfall amount will decline to around 1.97 mm for the duration of 2070-2099. The decrease in rainfall amount will be aggravated by increased evapotranspiration rates caused by likely mounting temperatures and aridity. The mean annual temperature will rise to 26.9^{o}C during 2070-2099 (Cline, 2007: cited by MoA, 2011)

On the other hand, the National Metrological Agency (1986) revealed that in Ethiopia climate variability and change in the country is mainly manifested through the variability and decreasing trend in rainfall and increasing trend in temperature. Besides, rainfall and temperature patterns show large regional differences (NMA, 2007).

2.2.4. Impacts of climate change on crop biophysical growth of crops

Climate change affects crop production through direct impacts on the biophysical growth of crops. Among the various environmental changes brought about by the climate change that limit crop yields, heat and water stresses are considered the most important (Prasad et *al.*, 2008). Heat stress during developmental phases lead to fewer and smaller organs, reduced light interception due to shortened crop life, and altered carbon assimilation processes including transpiration, photosynthesis, and respiration (Stone, 2001). Heat stress during flowering and grain filling stages results in decreased grain count and weight, resulting in low crop yield and quality (Bita and Gerats, 2013)

The rising temperatures, carbon dioxide levels and uncertainties in rainfall associated with global warming may have serious direct and indirect impacts on crop production. A loss of crop production is predicted in all over the world by the end of this century due to climate change if action is not taken (Manju et al, 2015). Temperatures exceeding the optimal level for biological processes cause a steep drop in net growth and yield. Production of annual crops will be affected globally by the expected increase of 2–4 ^{o}C in mean temperatures towards the end of the 21st century.

At the same time, higher rainfall could enhance growing period duration. Also, the higher CO_2 concentrations in the atmosphere under changed climatic conditions might act as aerial fertilizer and boost crop growth. All such conflicting factors should be taken into consideration while assessing the climate sensitivity of agriculture.

Carbon dioxide is the essential element for photosynthesis, in which CO_2 and water converted in to sugars driven by the energy from light. Photosynthesis proceeds in the green pigments of leaves, and CO_2 has entered into the leaves through the stomatal openings where it is taken up in the cells surrounding the stomatal cavity. The opening of the stomata compromise between CO_2 to enter and vapor to escape. The stomata are close partly under photosynthesis. Water stress induce also partial closure of stomata.

According to (Allen, and Prasad, 2004) an increase in CO_2 concentrations causes a partial closure of stomata which reduces water loss by transpiration and improves water use efficiency. This effect leads to an improved performance and yield of C3 (wheat) and C4 (sorghum) plants even in a condition of mild water stress. Experiments show that crop performance at elevated CO_2 concentration shows a positive but variable increase in productivity for annual crops. Annual C3 plants exhibits an increased production averaging about 30% at doubled CO_2 concentration.

Experiments for C3 plants (wheat, soybean, barley) show, the present day atmospheric CO_2 concentration levels strongly limit the rate of CO_2 fixation in photosynthesis. The C3 pathway coexists the photo respiratory pathway. Plants with C4 photosynthetic path way show a smaller response to elevated CO_2 than C3 plant pathway and transpiration in C4 plants is controlled and WUE is induced for those plants.

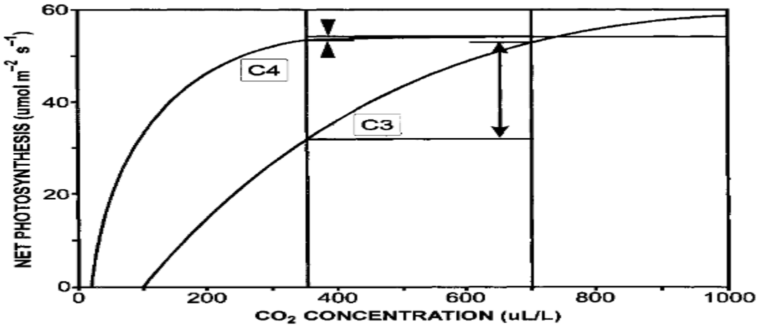


Figure 4: Net photosynthesis of typical C3 and C4 plants Vs. CO_2 concentration

Temperature is central to how climate influences the growth and yield of crops. The rate of many growth and development processes of crop plants is controlled by air or soil temperature. Over the last decade or so, the interests of the scientific community in the response of crops to temperature has been renewed as the evidence of a warming of global mean temperatures due to human activities becomes more persuasive. Increasing temperature declines annual crop yield by shortening growing length. ((Allen and Prasad, 2004)

Temperature determines the length of growing season of crops by determining the crops germination, vegetative and reproductive stages (FAO, 2009). Increased temperatures lead to increased evapotranspiration which thus affecting water availability which is very important in the process of photosynthesis (Rasul et al, 2010). Generally, high temperature affects the chloroplasts where photosynthesis takes place through generation of reactive oxygen species and low temperatures also affect crops by reducing their metabolic reactions. Different crops have different optimum temperature:

2.2.5. Climate change adaptation (CCA) for sorghum and wheat

Adaptation has the potential to reduce the negative impacts of CC on agriculture (Adger *et al*., 2003; IPCC, 2014; Hassan and Nhemachena, 2008; Tingem et al., 2009). Adaptation is a site-specific phenomenon and hence requires local analysis for better understanding (Deressa *et al*., 2008; Boko *et al*., 2007) because it varies according to systems in which they occur, who undertakes them, climatic shocks that cause them, their timing, functions, forms and effects. Currently, economic planning and policy decision-making has become particularly tricky for economies in SSA due to increasing climate variability (Brown *et al*., 2010). Conventional wisdom suggests that investments that reduce current impacts of climate variability are likely to be the best adaptation decisions a planner can make. It is crucial that any policy decisions to support their implementation are informed by a synthesis of the best available evidence from research findings. Adaptation strategies are very essential, and must be developed within an economic context (IPCC, 2007; IPCC, 2014).

Adapting to climate change is, inevitably, a complex process as the phenomenon of climate change itself. Each of the various impacts needs to be assessed and the most appropriate countermeasures designed, taking account of effectiveness, costs and socio-political acceptability (Conway, 2009).

Throughout history, people and societies have adjusted to and coped with climate, climate variability, and extremes, with varying degrees of success. This section focuses on adaptive human responses to observed and projected climate-change impacts, which can also address broader risk-reduction and development objectives (IPCC, 2014).

To avoid or at least to reduce negative effects and exploit possible positive effects several agronomic adaptation strategies for agriculture have been suggested. A number of different methods for studying adaptation to climate change have been applied in literature (Mendelsohn and Dinar, 2004). These include the testing of adaptation options as specified in agro-ecosystem models, possibly linked with farm level economic.

2.3. Crop Growth Simulation Models

A Crop simulation model is a set of mathematical equations describing a bio-physical system (soil–plant–atmosphere). Crop simulation models predict the response of crops to weather, soil, and management by simulating the growth and development of plant organs such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant. Changes in climatic conditions influence soil moisture availability, nutrients and water uptake by plant root. The phenology of the crop is also affected and, depending on the growth stage of a plant, unfavorable climatic conditions can result in large losses in crop yield or total crop failure (Thornton *et al.*, 2009; Nangia *et al.*, 2010; Liu *et al.*, 2013).

In recent years, crop growth models have become state-of the art of research tools and are an important component of agriculture-related decision-support systems (Mavromatis et al 2001; Jones *et al.*, 2003). These models serve as a research tool for evaluating optimum management of cultural practices, fertilizer use, and water use. Modeling crop yield response to management options and prevailing environmental conditions can be done through empirical and process-based (simulation) models and each approach have its merits and limitations.

Crop simulation models are complementary tools in field experiments to develop innovative crop management systems, which considers the complex interactions between weather, soil properties and management factors that influence crop performance (Ahmed and Hassan, 2011). The author further noted that crop modeling is becoming a valuable tool to understand

and mimic climatic constraints and yield gaps. Different crop modeling studies clearly depicted that models are more appropriate and can be parameterized to simulate crop growth under a changing climate scenarios to select suitable genotypes, sowing time, cropping pattern, fertilizer and weed management strategies enabling crop to cope with environmental hazards as potential agronomic and decision making tool (Jones et al., 2003; Butt et al., 2005).

Crop simulation models utilize in-built algorithms that express the relationship between plant growth processes (photosynthesis, transpiration, phenological developments, plant water uptake and biomass growth and partitioning) and environmental driving forces (e.g., soil water availability, daily temperature and photoperiod). Also peculiar to crop models is the integration of factors that are cultivar-specific "genetic coefficients" to estimate daily growth and response of plants to environmental factors such as weather, soil and management practices (Boote et al., 1998).

The crop models also have the capability of simulating the yield of a range of crops in response to various climate scenarios thereby providing insights into the impact of management strategies on the productivity due to future climate change **(**Tachie, 2010)

3. MATERIAL AND METHODS

3.1. Description of Study Site

Geographical Location: The study was carried out in Amhara and Tigray National Regional States of Ethiopia. Figure 4 shows the location of the study areas. Sirinka and Kobo from Amhara National Regional State and Enderta from wheat growing district of Tigray National Regional State were selected. Two crop types, sorghum and wheat, were selected for this study. Sirinka is situated between 11^{o}41’ and 11^{o}49’N latitude; and 39^{o}07’ and 39^{o}42’E longitude with elevation 1749 - 2033 m.a.s.l. Kobo is located between 12°09′N and 12.15°N latitude and between 39.38^{0}E and 39.63°E longitude with elevation of 1468 m.a.s.l. And Enderta study site is located between 13.22^{o}N and 13.35^{o}N latitude and 39.29^{o}E to 39.36^{o}E longitude and has an elevation of 1500 to 2300 m.a.s.l.

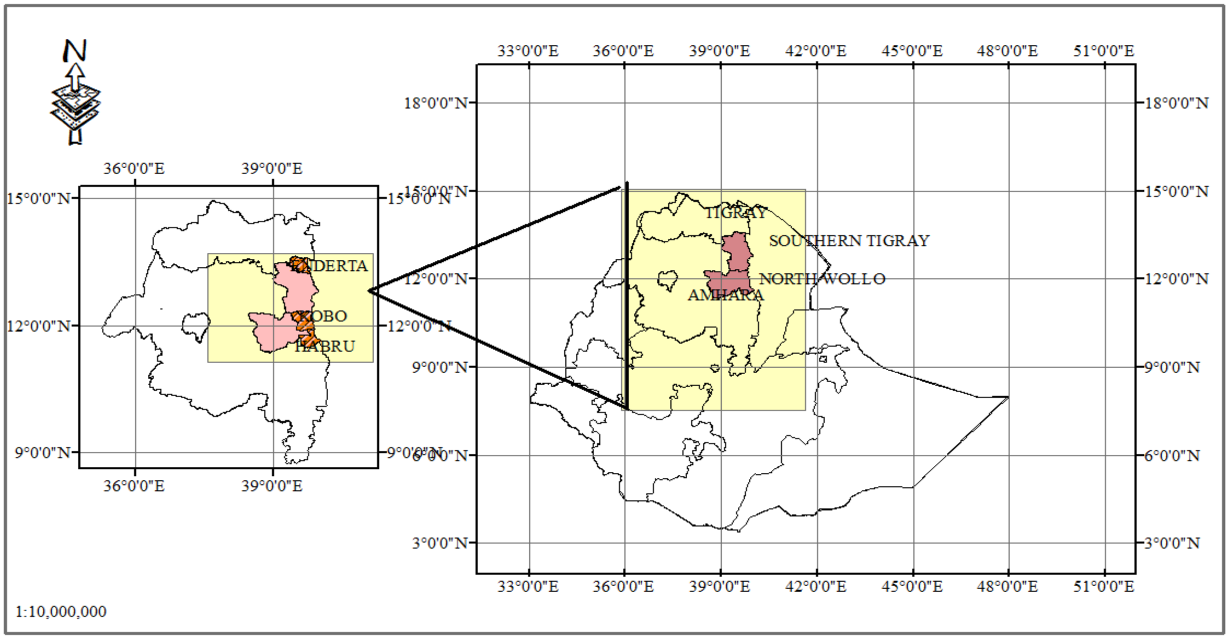


Figure 5. Map of study sites (Kobo, Sirinka and Enderta)

Climate of the study area: In general, the study area has a semi-arid climatic condition, a general characteristic feature of the northern part of the country. Based on the traditional classification system, the study sites lie from *Kola* to *Woynadega* agro-ecological zones. More specifically, Kobo district is categorized under Kolla while Sirinka and Mekelle districts are grouped under Woynadega agro-ecological zones. Regarding rainfall distribution, Kobo and Sirinka receive bimodal rainfall type with the highest peak during JJAS season a small peak during FMAM season (locally known as *belg*). On the other hand, rainfall in Mekelle is concentrated mainly during June to September with small showers occur during February to May. Table:3 depicts the seasonal and annual rainfall amounts and mean annual temperature of the study sites.

Table 4. Annual and seasonal rainfall and temperatures of the study area (based on 1985 to 2014 observed climate data for Kobo and Sirinka and 1980 to 2010 for Enderta)

Site	Mean Temperature (^{o}c)	Rainfall		
		Belg (mm)	*Kiremt* (mm)	*Annual* (mm)
Sirinka	20.1	300.1	586.5	1036.9
Kobo	22.6	117.3	401	699.9
Mekelle	15.3	81.5	517	607

3.2. Data Collection and Handling

3.2.1. Soil Data

Soil data for the study sites were obtained from different sources. Soil data for Enderta was obtained from Gebre et al., (2014). Similarly, data for Sirinka was from Adem Mohammed, a PhD student at Haramaya University. Likewise, for Kobo site, the soil data were obtained from Ethiopian Institutes of Agricultural Research (EIAR). Table 4-5 reveals soil data of the experimental sites. Bulk density(BD), drained upper limit (DUL), drained lower limit (DLL), saturation (SAT), root growth factor (RGF) and saturated hydraulic conductivity (SKS) soil parameters were estimated from soil texture data automatically using Decision Support System for Agro-technology Transfer (DSSAT4.6) SBUILD software package.

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Table 5. Soil physical and chemical characteristics at Kobo

Depth	Particle Size Analysis (%)				PH 1:2.5H2O	EC	Total N	OC	CEC
Cm	% Sand	% Silt	% Clay	Class		ds/m	%	%	meq/100g soil
0-15	21	49	30	clay loam	7.6	2.04	0.07	0.90	51.31
15-30	31	59	10	silt loam	7.76	0.38	0.09	1.03	53.45
30-45	33	59	8	silt loam	7.56	0.69	0.07	1.23	56.92
45-60	27	65	8	silt loam	7.61	1.21	0.09	1.10	50.08
60-75	25	65	10	silt loam	7.69	0.16	0.07	1.15	53.35
75-90	23	57	20	silt loam	7.8	0.10	0.12	1.65	56.00
90-105	21	59	20	silt loam	7.98	0.87	0.15	1.22	57.43

(Source: Ethiopian Institutes of Agricultural Research, Climate and Geospatial Research Directorate, 2012)

Table 6. Soil physical and chemical characteristics at Mekelle

Layer (cm)	Sand (%)	Silt (%)	Clay (%)	BD (g/cm3)	Total N (%)	CEC (meq/100g soil)	pH	EC (dS/m)	OM (%)	OC (%)
0-20	40	28	32	1.41	0.07	29.2	7.71	0.8	2.39	1.38
20-65	44	22	34	1.45	0.07	35.6	7.81	0.85	2.27	1.32
65-107	51	17	32	1.46	0.06	41.5	7.68	2.05	1.78	1.03
107-147	55	16	29	1.47	0.06	39.5	7.65	2.3	1.50	0.87
147-200	40	32	28	1.50	0.05	29.5	7.97	1.30	1.09	0.63

(Source: Gebre et al., 2014)

OC- Percentage Organic carbon, Total N- Percentage Nitrogen, EC- Electric conductivity, CEC- Cation exchange capacity, OM- Organic Matter, BD- Bulk Density

Table 7. Soil physical and chemical characteristics of Sirinka

Layer (cm)	OC (%)	N (%)	SA (%)	CL (%)	SI (%)	p^H in H_2O	LL (cm^3 cm^1)	DUL (c^3 cm^{-3})	SAT (cm^3 cm^{-3})	RGF (0-1)	SKS (cm h-1)	BDM (g/cm3)
30	1.23	0.16	12.5	55.0	32.5	5.9	0.335	0.494	0.540	1.0	0.06	1.24
60	0.72	0.18	15.0	52.5	32.5	6.3	0.308	0.454	0.498	0.407	0.06	1.29
105	0.42	0.13	27.5	37.5	35.0	*6.4*	0.225	0.359	0.459	0.192	0.23	1.36
175	0.30	0.08	22.5	35.0	42.5	6.4	0.209	0.354	0.478	0.061	0.23	1.31
200	0.28	0.08	25.0	32.0	43.0	6.5	0.194	0.337	0.471	0.024	0.23	1.33

(Source: Adem Mohammed, Haramaya University, PhD student)

OC- Percentage Organic carbon, CL- Percentage Clay, SI- Percentage Silt, N-Percentage total Nitrogen, SA- Percentage Sand, DUL- Drained Upper limit, LL- Lower limit, SAT- Saturation, RGF- Root growth factor, SKS- Saturated Hydraulic conduction, BDM- Bulk Density

3.2.2. Crop and Management Data

Commonly grown varieties of sorghum (Teshale and Melkam) and wheat (Mekele-1) were used as a testing crops. Teshale and Melkam are mainly early-medium maturing groups released for areas characteristically affected by terminal drought. Similarly, Mekele-1 is an early maturing group released for moisture stress areas. Sorghum experimental data related to cultivar specific phenological and growth characteristic, yield and yield component data as well as field management practices were obtained from Melkassa Agricultural Research Center (MARC). Likewise, wheat experimental data related to phenological, growth, yield and yield components of mekele-1 wheat cultivar was obtained from Mekelle Regional Agricultural Research Center (MRARC). Crop and management data collected at each site is described in Table 7.

Table 8: Crop management data

Crop type	Variety Name	Experiment conducted		Fertilizer application		Source
		Site	Year	Type	Amount	
Sorghum	Melkam	Kobo	2007,2008, 2010, 2011, 2013	DAP Urea	100kg/ha 50kg	EIAR
	Teshale	Kobo	2005, 2007, 2008, 2010 2011, 2013	DAP Urea	100kg/ha 50kg	
Wheat	Mekele-1	Mekelle	2011, 2012, 2014	DAP Urea	100kg/ha 50kg	MARC (Mekele)

3.2.3. Climate Data

3.2.3.1. *Long term observed data*

Historical daily climate data 1985-2014 (Rainfall, maximum and minimum temperatures) for Sirinka and Kobo observatory stations were obtained from Ethiopian Institute of Agricultural Research (EIAR). Whereas, for Enderta site, Mekele aviation observatory station was used and long year climate data (1980-2010) was obtained from National Meteorology Agency (NMA) of Ethiopia. Solar radiation data was estimated from air temperature and latitude data using DSSAT4.6 weather module.

3.2.3.2. *Future climate data*

Site specific climate change scenario data for the study sites were downscaled using Agricultural Model Inter-comparison and Improvement Project (AgMIP) climate scenario generation scripts for 20-global climate models (20-GCM's) from the ready-made data sets for east Africa region (Asseng et al., 2013). In this study, the outputs of IPCC fifth assessment report (AR5), which referred Representative Concentration Pathway's (RCP's) were used to downscale site specific climate change scenario data. The GCM's used for this study were obtained from (AgMIP) east African team, Climate and Geospatial Research Directorate (CGRD) of Ethiopian Institutes of Agricultural Research (EIAR), participated on "Climate change and variability impact assessment of east African agriculture" lead by International Crop Research Institute for Semi-Arid Tropics (ICRISAT). The scenarios were developed for two RCP's (RCP4.5 and RCP8.5) scenarios using a delta based downscaling approach. The delta method produces a smoothed (interpolated) surface of changes in climates (deltas or anomalies) and then applies this interpolated surface to the baseline climate (Hijmans et al., 2005). For model biases, the delta method adopts that the future mean and variability of climate will be the same as those in present day simulations (Mote and Salathe, 2009). Table 8 shows the descriptions of the GCM's considered for this study.

The model was used to downscale both temperature (minimum and maximum) and rainfall data of future climate at each site. After arranging the data, future climate of the study sites was analyzed for two time slices centered in the 2050s (2040-2069) and 2080s (2070-2099) and compared with the base period of the respective sites. In this case, the absolute differences between means in temperature and percentage change in precipitation were used to describe future climate change with respect to the base period.

Table 9. Coupled Model Inter-comparison Project phase 5 (CMIP5) general circulation models (GCM’s) used for this study

No	**Modelling center**	**Country**	**Model**	**Lat.**	**Lon**	**Res.**
1	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology (CSIRO-BOM)	Australia	ACCESS1.0	1.87	1.25	MR
2	Beijing Climate Centre, China Meteorological Administration	China	BCC-SM1.1	2.81	2.79	LR
3	College of Global Change and Earth System Science, Beijing Normal University	China	BNU-ESM	2.81	2.79	LR
4	Community Climate System Model, Climate and Global Dynamics Division/ National Centre for Atmospheric Research	USA	CCSM4			
5	Community Earth System Model, Climate and Global Dynamics Division/ National Centre for Atmospheric Research	USA	CESM1-BGC			
6	Commonwealth Scientific and Industrial Research organization/Queensland Climate Change Centre of Excellence (QCCCE)	Australia	CSIRO-Mk3.6	1.87	1.87	MR
	Canadian Centre for Climate Modelling and Analysis	Canada	CanESM2	2.81	2.79	LR
7	Geophysical Fluid Dynamics Laboratory	US-NJ	GFDL-SM2G 2	2.5	2.0	LR
		US-NJ	GFDL-ESM2M	2.5	2.0	LR
8	Met Office Hadley Centre	UK-Exeter	HadGEM2-CC	1.87	1.25	MR
		UK-Exeter	HadGEM2-ES	1.75	1.25	MR
9	Institute Pierre-Simon Laplace	France	IPSL-CM5A-LR	3.75	1.89	LR
			IPSL-CM5A-MR	2.50	1.26	LR
10	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology	Japan	MIROC-ESM	2.81	2.79	LR
		Japan	MIROC5	1.40	1.40	HR
11	Max Planck Institute for Meteorology (MPI-M)	Germany	MPI-ESM-	1.87	1.87	LR
		Germany	MPI-ESM-MR	1.87	1.87	MR
12	Meteorological Research Institute	Japan	MRI-GCM3-	1.12	1.12	HR
13	Norwegian Climate Centre	Norway	Nor-ESM1-M	2.50	1.89	LR
14	Institute for Numerical Mathematics	Russia	INM-CM4	2.0	1.5	MR

3.3. Data Analysis

Data quality control: The data were subjected for quality visualization and inspections using RClimDex1.0 to detect potential problems that cause changes in the seasonal cycle or variance of the data (Abbas *et al*., 2013). The main purpose of this software in quality control was to identify errors in data processing, such as errors in manual keying, daily precipitation amounts less than zero (if any) and diurnal temperature difference is negative. Under this study the data with such problems were removed and set to a missing value. Outliers in daily maximum and minimum temperature were also assessed and values outside a range of mean ± 4 × STD were also removed set as a missing value (Zhang *et al*., 2005). Homogeneity test was also carried out using RHtestV4 software package in case where the station has been moved to another location and a change in recording equipment during the recording period.

3.3.1. Climate Variability Analysis

Daily rainfall and temperature time series data were captured into MS Excel spread-sheet and summarized in to annual and seasonal rainfall totals and average temperatures. Then, data was subjected to different variability and trend analysis. The Coefficient of Variance (CV) statistics were utilized to test the level of mean variation of annual and seasonal rainfall amount and calculated using the following formula.

$$CV = \frac{s}{\bar{x}} * 100 .$$

Where CV= Coefficient of variation, S=standard deviation of the time series and ẍ= mean of the time series

3.3.2. Trend Analysis

To estimate the sign and slope of long term mean annual and seasonal rainfall and temperature for the selected study sites, Mann-Kendall's trend test and Sen's slope estimation method were used.

3.3.2.1. Mann-Kendall' test

The Mann-Kendall's test was employed to detect trends of the temperature and precipitation of each site. Mann-Kendall's test is a non-parametric method, which is less sensitive to outliers and test for a trend in a time series without specifying whether the trend is linear or nonlinear (Partal and Kahya, 2006; Yenigun *et al*., 2008). The Mann-Kendall's test statistic is given as:

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

Where S is the Mann-Kendal’s test statistics; x_i and x_j are the sequential data values of the time series in the years *i* and *j* (*j* > *i*) and *N* is the length of the time series. A positive *S* value indicates an increasing trend and a negative value indicates a decreasing trend in the data series. The sign function is given as

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

The variance of *S*, for the situation where there may be ties (i.e., equal values) in the *x* values, is given by

$$Var\,(S) = \frac{1}{18}\left[N(N-1)\,(2N+5) - \sum_{i=1}^{m} t_i\ (t_i - 1)\,(2t_i + 5) \right]$$

where, *m* is the number of tied groups in the data set and t_i is the number of data points in the i^{th} tied group. For n larger than 10, Z_{MK} approximates the standard normal distribution (Partal and Kahya, 2006) and computed as follows.

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{Var\,(S)}} & if \ \ S > 0 \\ 0 & if \quad S = 0 \\ \dfrac{S+1}{\sqrt{Var\,(S)}} & if \ \ S < 0 \end{cases}$$

The presence of a statistically significant trend is evaluated using the Z_{MK} value. In a two-sided test for trend, the null hypothesis *Ho* should be accepted if $\left|Z_{MK}\right| < Z_{1-\alpha/2}$ at a given level of significance. $Z_{1-\alpha/2}$ is the critical value of Z_{MK} from the standard normal table. E.g. for 5% significance level, the value of $Z_{1-\alpha/2}$ is 1.96.

3.3.2.2. Sen’s estimator

If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple non-parametric procedure developed by Sen (1968b). The slope estimates of N pairs of data are first computed by

$$Ti = \frac{(Xj - Xi)}{j - k},$$

i=1, 2……………. N

where X_j and X_k are data values at times j and k (j>k), respectively. The median of these N values of Qi is Sen’s estimator of slope. If N is odd, then Sen’s estimator is computed as Qmed=(N+1)/2 and if N is even then, Sen’s estimator of slope is computed as Qmed= [(N/2) + ((N+2)/2)]/2. Finally, Qmed is tested by a two sided test at the 100(1 – a) % of confidence interval (Mondal *et al.*, 2012). The positive or negative slope *Qi* is obtained as upward (increasing) or downward (decreasing) trend.

3.3.3. Crop Model

In order to investigate the impact of future climate change, the Decision Support System for Agro-technology Transfer (DSSAT) was used to stimulate growth, development and yield of wheat and sorghum. DSSAT is a suite of crop models developed to simulate growth, development and yield of several crops and changes in soil water, carbon and nitrogen balances that take place under the cropping system over time (Jones *et al.*, 2003). DSSAT is uses common modules for soil dynamics and soil–plant–atmosphere interactions regardless of the plant growth module selected.

In this study, CERES-Wheat and CERES-Sorghum crop models (Jones *et al.*, 2003), which are embedded within the DSSAT version 4.6 (Hoogenboom *et al.*, 2009), were used to simulate daily phenological development and growth of wheat and sorghum, respectively in response to environmental and management factors. The CERES-Wheat and CERES-Sorghum model employs soil data, crop management data and daily meteorological data as input to simulate daily leaf area index (LAI) and vegetation status parameters, biomass production and final yield. The daily meteorological data include solar radiation, rainfall, maximum and minimum air temperatures. The major soil data include soil type, slope and drainage characteristics, and chemical-physical parameters for each soil layer, such as saturated soil water content (SWCON), lower drained limit, upper drained limit, initial soil water content, relative root distribution, soil pH, bulk density and soil organic matter. The crop management data include variety, planting date, plant density, irrigation and fertilizer (application rates and dates). Crop genetic coefficients included in the model related to photoperiod sensitivity (thermal time), duration and rate of grain filling, conversion of mass to grain number and vernalization requirements (Ritchie *et al.*, 1998). The model calculates the phasic and morphological development of the crops using temperature, day length and genetic characteristics. The water and nitrogen balance sub models, on the other hand, provide feedback that influences developmental and growth processes (Ritchie *et al.*, 1998).

DSSAT have been used for more than 20 years by researchers, educators, consultants, extension agents, growers, policy and decision makers over 100 countries worldwide (Jones et al., 2003*)* and used for many applications ranging from on-farm and precision management to regional assessment for the impacts of climate change and variability (Jones *et al.*, 2003).

3.3.3.1. Model calibration and evaluation

Model calibration is the adjustment of parameters so that simulated values compare fairly well with observed ones (Timsina and Humphreys, 2006). In order to simulate accurately, a model needs to be calibrated for the soil properties, climatic characteristics and plant growth parameters of the site and crops simulated. In the CERES-Wheat and CERES-Sorghum models, in addition to the species and eco-type parameters, six and seven genetic coefficients, profoundly for sorghum and wheat are required for defining the traits that differentiate between cultivars within a crop species (Jones *et al*., 2003). In this study, two-year data (2007 and 2008) for Melkam, three-year data (2005, 2007 and 2008) for Teshale and one-year data (2011) for Mekelle-1 varieties collected from an experiment conducted at Kobo and Enderta, for sorghum and wheat crops respectively was used to calibrate CERES-Sorghum and CERES-Wheat models.

The Genetic coefficient calculator (GENCALC) is used to estimate genotype specific coefficient for DSSAT crop model (Hunt *et al*., 1993; Jones *et al*., 2003). In GENCALC, the coefficients of a genotype are estimated iteratively by running the appropriate crop model with model input data sets. To estimate the genotype coefficients of a specific cultivar, a base cultivar coefficient existed in the model and resembles similarity in maturity group of the intended cultivar was selected first. Accordingly, cultivar 'CARGIL_1090' was used to simulate the initial run to estimate/calculate growth and development related genotype coefficients of Melkam and Teshale while cultivar 'MANTOU' for Mekelle-1. Then, the GENCALC calculates the appropriate genotype coefficients by integrating the real observed data sets (soil, weather and crop field management data) for specific cultivar. GENCALC was iteratively run until the model simulates fairly the observed data set. The coefficients are determined in a specified sequence starting with those that relate to development aspects. Finally, the genetic coefficient determined for each crop are depicted in Table 9 and 10.

Table 10. Estimated Genetic Coefficients values for Sorghum cultivars (Teshale and Melkam) at Kobo site, northern Ethiopia

Genetic parameters	Description	Initial coef.	Estimated coef.	
		CARGIL_1090	Teshale	Melkam
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod	460.0	250.1	311.7
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced	12.50	12.46	12.46
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20.	90.0	101.7	154.4
P5	Thermal time (degree days above a base temperature of 8°C) from beginning of grain filling (3 - 4 days after flowering) to physiological maturity	600.0	492.8	480.8
G1	Scaler for relative leaf size	5.0	5.512	6.4
G2	Scaler for partitioning of assimilates to the panicle (head).	6.0	5.255	5.0

Table 11: Estimated Genetic Coefficient values for wheat cultivar (Mekele-1)

Genetic coefficient parameters	Definitions	Initial coef.	Estimated Coef.
		MANITOU	Mekele-1
P1V	Days, Optimum vernalizing temperature, required for vernalization	8	8
P1D	Photoperiod response (% reduction in rate/10h drop in pp)	100	2.1
P5	Grain filling (excluding lag) phase duration (^{o}C.d)	320	580.2
G1	Kernel number per unit canopy weight at anthesis (#/g)	23	49.8
G2	Standard kernel size under optimum condition (mg)	23	79.8
G3	Standard non stressed mature tiller wt (incl grain) (g dwt)	2.5	2.5
PHINT	Interval between successive tip appearance (^{o}C.d)	86	150

Model evaluation: the performance of the model was evaluated to assess the established genotype values of the model representing the observed values. The coefficient of determination (R^2), root mean square error (RMSE) and index of agreement or d-statistic were employed as statistical indicators to evaluate the performance of the model.

The Root Mean Square Error (RMSE) were computed to measure the coincidence between measured and simulated values. The comparison has been done with simulated mean values of days to flowering, days to maturity and grain yield (kg/ ha) with measured ones. The value of RMSE approaching to zero indicates the goodness of fit between the simulated and observed values. The RMSE was computed using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

where n= number of observations, P_i= predicted value for the ith measurement and O_i= observed value for the ith measurement.

The RMSEn (the normalized root mean square error) was also used to evaluate the model performance and computed as follows:

$$RMSEn = \frac{RMSE \times 100}{\overline{O}}$$

where RMSE= root mean square error and $\overline{O}$ = the overall mean of observed values

RMSEn (%) gives a measure of the relative difference of simulated versus observed data. The simulation is considered excellent if the RMSEn is less than 10%, good if it is greater than 10% and less than 20%, fair if RMSEn is greater than 20% and less than 30%, and poor if the RMSEn is greater than 30% (Aronica *et al.*, 2002).

On the other hand, d-statistic provides a single index of model performance that encompasses bias and variability and is a better indicator of 1:1 prediction than R^2. The closer the index value is to unity, the better the agreement between the two variables that are being compared and vice versa (Willmott *et al.,* 1982). The d-statistic was computed as:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(|P'_i| + |O'_i| \right)^2} \right], 0<d<1$$

where n: number of observations, P_i= predicted value for the ith measurement, O_i= observed value for the ith measurement, $\overline{O}$ = the overall mean of observed values, $P'_i = P_i - \overline{O}$; $O'_i = O_i - \overline{O}$.

Moreover, linear regression was applied between simulations and observations to evaluate model performance and correlation coefficient (R^2) for each simulation (Loague and Green,1991).

3.3.3.2. Model validation

Model validation is a confirmation that crop models accurately reproduce the experiential data (Hoogenboom *et al*. 2003) which is carried out using independent (not used during calibration) data set. Accordingly, the CERES-Sorghum and CERES-wheat models were validated with rain-fed experiment data collected during 2010 to 2013 for sorghum and 2012 and 2014 for wheat in their respective sites. The model was validated by comparing the simulated values of development and growth characteristics of each crop with their corresponding observed values, and by calculating statistical parameters of an agreement between simulated and observed values. The statistical indicators such as coefficient of determination (R^2), RMSE and Index of agreement (d-statistic)) were computed to determine the degree of predictability. For model performance evaluation, the statistical indicators used during model calibration were fully applied (Willmott, 1982; Soler *et al*., 2007) using the equations presented under model calibration processes.

3.3.4. Climate Change Adaptation

To alleviate the expected adverse impacts of climate change through adaptation practices, identification and characterization of adaptation options is the first step (Bryant *et al*. 2000; Smit *et al*., 2000). To identify the best adaptation practices, CERES-Sorghum and CERES-Wheat models were used to evaluate the impacts of different adaptation options under future climate. Management practices were used to evaluate yield response of sorghum and wheat under a projected future climate are presented in detail in the following section.

3.3.4.1. Planting date

Different studies used different approaches to set planting dates for crop simulation studies. However, for this study the approach of optimizing planting date was used to which leads to highest simulated crop yield (Soler *et al*., 2008; Waha *et al*., 2012). According to Alamirew *et al*. (2002) the time of sowing for sorghum and wheat in JJAS (*meher)* season ranges from mid-June to August depending on soil type, the level of rainfall and the varieties used. Accordingly, three planting window options (16-June to 30-June, 1-July to 15-Jul and 16-July to 30-July) were assumed to evaluate the response of sorghum and wheat production for the projected climate change scenarios in the study location.

3.3.4.2. Plant population

To determine the optimum plant population of sorghum and wheat production using projected climate change scenarios, evaluation was carried out by varying plant population from the average plant population used during experimentation. For sorghum 6 plants/m^2, 7 plants/m^2, 8 plants/m^2 and 9 plants/m^2 and for wheat 150 plants/m^2, 250 plants/m^2, 300 plants/m^2 were used to determine the optimum plant population using simulation modeling.

3.3.4.3. Fertilizer application rate

For this study, three levels of nitrogen fertilization rates were simulated under the projected future climate change scenario. Table 11 presents the nitrogen fertilization treatments used to determine the optimum nitrogen fertilization rate.

Table 12. fertilization rate (nitrogen) treatments for future sorghum and wheat production

Nutrient Type	Treatment-1		Treatment-2		Treatment-3	
	DAP (150 kg/ha)	Urea (100 kg/ha)	DAP (100 kg/ha)	Urea (75 kg/ha)	DAP (75 kg/ha)	Urea (50 kg/ha)
N-kg/ha	27	46	18	35	14	23
P-kg/ha	69		46		35	

Finally, for comparison purpose, historic yield of wheat (1981-2010) and sorghum (1985-2014) were simulated and used as baseline yield data. In this case, daily weather data obtained from Mekelle, Sirinka and Kobo stations were used. In addition, future projected climate data downscaled from the 20 GCMs under two RCPs in each site was also used as an input for DSSAT to generate crop yields for two time slices centered in the 2050s (2040-2069) and 2080s (2070-2099). Finally, the performance of both crops with the prescribed changes was compared with the baseline as follows.

$$\Delta yield = \frac{Y_{predicted} - Y_{base}}{Y_{base}} x100$$

where $Y_{predicted}$ is predicted yield (kg ha^{-1}), Y_{base} is yield of the base period (kg ha^{-1}) and Δ_{yield} is the yield difference (%).

3.3.5. Model Sensitivity Test

To identify which climate variable do affect the production of sorghum and wheat, model sensitivity test was conducted using simulation matrix under DSSAT4.6. The input parameters and their variability used to run sensitivity analysis is presented in Table 12.

Table 13. Climate change/variations considered for sensitivity analysis

Parameters	Change/expected amount (for CO_2)	Remark
Temperature Change	2ºC, 3ºC and 4.5ºC	Change from the baseline climate
Rainfall	+-10%RF	Deviation from the baseline climate
Atmospheric CO2	540ppm and 750ppm for RCP4.5 and RCP8.5 respectively	Expected atmospheric CO_2 level at the end of the century

4. RESULT AND DISSCUSSION

4.1. Past and Future Climate Variability and Trends

4.1.1. Past Rainfall Variability and Trends

Mean annual and seasonal rainfall for Kobo, Sirinka and Mekelle during the last three decades is depicted in Table 13. The result revealed that the stations under investigation received different annual rainfall amount; the highest being recorded at Sirinka while the lowest was at Mekelle. Similarly, the amount of rainfall both during JJAS (*Kiremt*) and FMAM (*Belg*) seasons also varied among stations. In line with this, Meze-Hausken (2004); Gebre *et al*, (2013); Tagel and van der Veen (2013) reported that rainfall in northern Ethiopia is highly variable both in temporal and spatial scales.

The coefficient of variation in most stations revealed that rainfall in the area has moderate inter-annual variability (Table 13). The result indicated that *Kiremt* rainfall variability for the study stations was high (CV nearly >30%) over the last three decades. The present result is in corroboration with that of Gebre *et al*. (2013); Tagel and Van der Veen (2013); Bewket and Conway (2007) who reported a moderate inter seasonal variability of *kiremt* rainfall in northern Ethiopia. Likewise, *belg* rainfall also showed high inter annual variability. Comparing to JJAS seasonal variability of rainfall in the study stations, *belg* rainfall is more variable than the *kiremt* rainfall (CV=>30%). Seleshi and Zanke (2004); Bewket and Conway (2007) also reported similar results. Seleshi and Zanke (2004) noted that rainfall variability over the central highland of Ethiopia during *kiremt* season was associated with the equatorial eastern Pacific sea level pressure, the southern oscillation index and the sea surface temperature (SST) over the tropical eastern Pacific Ocean.

Table 14. Mean annual and seasonal rainfall (mm), coefficient of variation (CV %) and standard deviation for Kobo (1985-2014), Sirinka (1985-2014) and Mekelle station (1981-2010)

Station	**Annual rainfall**			**JJAS (*Kiremt*)**			**FMAM (*Belg*)**		
	Mean	**SD**	**CV (%)**	**Mean**	**SD**	**CV (%)**	**Mean**	**SD**	**CV (%)**
Kobo	685.9	155.7	22.7	449.1	143.7	32.0	160.4	73.9	46.1
Sirinka	1036.9	191.4	18.5	586.5	172.4	29.4	300.1	127.4	42.4
Mekelle	568.3	143.5	25.3	489.2	137.4	28.1	71.9	53.8	74.9

Figure 2 also presents the monthly rainfall distribution of the study stations. According to the study period, the stations were received rainfall during both *Kiremt* and *belg* seasons in different proportions. Accordingly, *Kiremt* (JJAS) season was contributed more than 55% of Sirinka and Kobos' annual total rainfall amount and more than 80% of Endertas' annual total rainfall amount. *Belg* rainfall also make a considerable contribution to the annual rainfall total at Kobo and Sirinka. Similarly, in the Amhara National Regional State of Ethiopia, *kiremt* and *belg* rainfall had contributed 55-85% and 8-24%, respectively to the annual rainfall totals (Bewket and Conway, 2007; Ayalew *et al*., 2012).

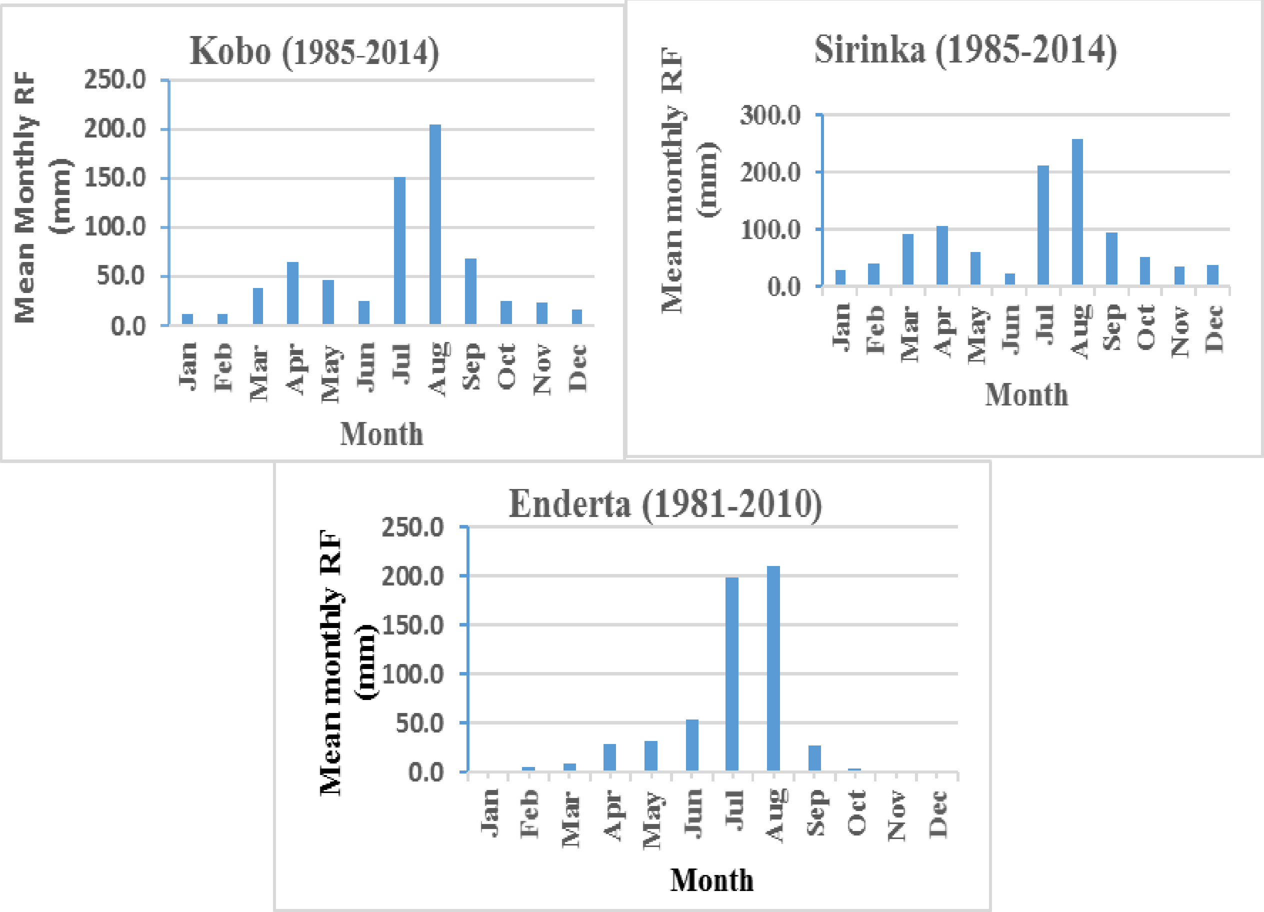

Figure 6. Mean monthly rainfall distribution at Kobo (1985-2014), Sirinka (1985-2014) and Enderta (1981-2010) sites.

Trends in observed annual and seasonal rainfall is displayed in Table 14. The result indicated an increasing trend annual and *Kiremt* (JJAS) season rainfall totals at Sirinka and Kobo during the last three decades. Nevertheless, the short rainy season at all studied stations and the annual and *Kiremt* rainfall totals at Enderta showed a declining trend. However, both increasing and decreasing trends of the annual and seasonal rainfall were not statistically significant. This result is in conformity with that of Gebre *et al*. (2013); Kassie *et al*. (2014); and Adisu *et al*. (2015) who reported a non-significant trend of annual and seasonal rainfall totals of different stations in north eastern parts of the country. The lack of significant trend in the study sites could due to observed high inter annual and seasonal variability. Inline of this a UNDP (2008) report indicated that strong inter-annual and inter-decadal variability of Ethiopia's rainfall make difficult for detection of long term trends.

Table 15. Trends of annual and seasonal (*Belg* and *Kiremt*) rainfall totals at Kobo, Sirinka and Mekele stations, northern Ethiopia (at 95% CI)

Station	Season	Mann-Kendall's trend test			Change (mm/30 Year)
		Kendall's Tau	Sen's slope	P Value	
Kobo	Annual	0.0065	0.1091	0.9731 ^{ns}	3.3
	FMAM	-0.2454	-1.2333	0.0547 ^{ns}	-37.0
	JJAS	0.1312	2.4588	0.3110 ^{ns}	73.8
Sirinka	Annual	0.0299	0.6000	0.8321 ^{ns}	18.0
	FMAM	-0.2598	-5.4300	0.0452*	-162.9
	JJAS	0.1908	6.3909	0.1449 ^{ns}	191.7
Mekele	Annual	-0.0943	-2.7471	0.4792 ^{ns}	-82.4
	FMAM	-0.0713	-0.4429	0.5959^{ns}	-13.3
	JJAS	-0.0713	-1.3091	0.5959^{ns}	-39.3

*= Significant

4.1.2. Past Temperature Variability and Trends

Statistical description of long term mean annual and seasonal temperatures at Kobo, Sirinka and Mekelle is presented in Table 15. The result indicated that mean annual and seasonal temperature at the studied stations varied depending on agro-ecological situations of the stations. Accordingly, the stations located at the lowland area (Kobo and Enderta) recorded higher mean annual and seasonal temperature than the station at the highland and midland (Sirinka). At all stations, higher mean air temperature was observed during *Kiremt* season than *Belg* season. In accordance with this, based on long term observed climate data for kobo (1985-2014), Sirinka (1985-2014), and Mekele (1981-2010), the annual mean surface temperature was 22.5, 20.1 and 17.7 ^{o}C, respectively.

Table 16. Summary of mean annual and seasonal (*Kiremt* and *Belg*) temperature over Kobo, Sirinka and Enderta (1985-2014 for Sirinka and Kobo; and 1980-2010 for Enderta)

Stations	**Annual temperature**			***Kiremt* temperature**			***Belg temperature***		
	Tmax	Tmin	**Mean**	Tmax	Tmin	**Mean**	Tmax	Tmin	**Mean**
Kobo	30.1	14.9	**22.5**	31.9	17.1	**24.5**	30.4	15.2	**22.8**
Sirinka	26.5	13.6	**20.1**	28.5	15.6	**22.0**	26.7	13.9	**20.3**
Mekele	23.6	11.7	**17.7**	24.7	12.5	**18.6**	26.0	13.3	**19.6**

Table 16 shows trends of annual and seasonal average temperatures at Kobo, Sirinka and Mekelle stations. The result revealed that both mean annual and seasonal temperatures of the studied stations increased over the study periods. However, based on Mann-Kendall's test statistics, the increasing trends of seasonal and annual temperature was statistically significant for both Kobo and Mekele stations but the change at Sirinka was not. In line with this, evidences suggested that Africa is warming faster than the global average and African drylands are likely to continue to warm (Boko *et al*., 2007). The result implied that increasing temperature load leads to higher rates of evapotranspiration and heat stress that in turn might limit crop yield potential (IPCC, 2014).

Table 17. Statistical results for Mann-Kendall's trend test at Sirinka, Kobo and Mekele stations for mean annual and seasonal temperature (1985-2014 for Sirinka and Kobo; and 1980-2010 for Enderta)

Station	Average air temperature	Mann-Kendall's trend test			Trend (^{o}C/decade)
		Kendall's Tau	Sens's slope	P Value	
Kobo	Annual	0.5846	0.05	< 0.0001	0.50
	Belg (FMAM)	0.4506	0.05	< 0.0001	0.50
	Kiremt (JJAS)	0.3594	0.039	< 0.0001	0.39
Sirinka	Annual	0.2407	0.012	0.0766	0.12^{ns}
	Belg (FMAM)	0.2368	0.022	0.0688	0.22^{ns}
	Kiremt (JJAS)	0.0529	0.0037	0.6974	0.04^{ns}
Mekelle	Annual	0.5494	0.039	<0.0001	0.39
	Belg (FMAM)	0.4459	0.042	0.0002	0.42
	Kiremt (JJAS)	0.4901	0.037	0.0008	0.37

4.1.3. Projected Rainfall and Temperature Changes

4.1.3.1. Projected Rainfall

Annual rainfall totals: projected change of annual rainfall totals in the study area is presented in Table 19. As compared to the base period, annual rainfall total is expected to increase in all stations by 2050s and 2080s. As a result, annual rainfall in the region will increase on average by 2.8% to 16.6% and by 8.4%-29% varied with emission scenarios and station by the 2050s and 2080s, respectively. On the other hand, the amount of annual rainfall expected to increase in the study area varies with location. In this regard, conditioned on emission scenarios considered, annual rainfall at Kobo, Sirinka and Mekelle is expected to increase by 8.5-15.6%, 12.2-16.6% and 2.4-8.4%, respectively by the 2050s. Likewise, by the 2080s, it is expected to increase by 8.6-17.8%, 10-29% and 8.4-15.3%, respectively at Kobo, Sirinka and Mekelle. In addition, the result revealed that annual rainfall is expected to increase for both periods (mid and end) periods of under the higher emission scenario (RCP8.5). However, the amount of change across stations and emission scenarios will have high variability among the GCMs employed. Nevertheless, the GCMs have no specific pattern or trend with that of the stations or emission scenarios.

Similar to the present study, different researchers in the country also revealed spatial variability of future rainfall in Ethiopia. For example, Zeray *et al*. (2007) and Tamiru *et al*. (2011) reported an increased trend of annual rainfall in Ziway and Meisso areas of Oromia Regional State of Ethiopia. On the other hand, Ayalew *et al*. (2012) indicated a decreasing trend of annual rainfall by the 2050s in different stations of the Amhara National Regional State of Ethiopia. Using multiple GCMs, Setegn *et al*. (2011) reported inconsistent trends of future rainfall totals at Adet, a station in Amhara National Regional State, considered climate models projected increases in rainfall. In addition to inherent spatial variability, the results from different studies could arise from the number and types of GCMs used to generate future rainfall conditions (Sarr, 2012). According to Conway and Schipper (2011), the direction and magnitude of annual rainfall projection over Ethiopia depend on the types of models employed to generate the future data.

According to Funk *et al*. (2005), the basic reason for the spatial, inter and intra annual variability of African climate is the warming and increased convection of the Southern Indian Ocean and would also remain as major climate variability drivers in the region. However, Conway (2009) and Conway and Schipper (2011) noted that despite clear evidence on the consequence of climate change, the drivers of African climate are poorly understood. Moreover, although Inter-Tropical Convergence Zone (ITCZ), the alternation of the monsoons, and the El Niño-Southern Oscillation of the Pacific Ocean are important derives of climate variability of Africa at present, it is poorly understood how they interact and how they are affected by climate change (Conway, 2009).

Table 18. Projected changes (%) in annual rainfall totals at Kobo, Srinka and Mekelle stations

GCMs	RCP4.5 MID			RCP4.5 END			RCP8.5 MID			RCP8.5 END		
	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle
ACCESS1	-1.8	-5.9	-4.7	-2.9	-2.5	-2	8.6	3	15	23.4	7.8	7.9
bcc-csm1	5.5	3.5	-7.4	-22.1	-4.9	-8.1	-4.2	2.9	-2.5	-10.7	13.6	9
BNU-ESM	30.8	40.8	27.7	33.9	58.3	42.4	38	54	22.7	34.2	63.5	50.8
CanESM2	3.9	18.5	12.7	6.8	26.6	13.5	19.4	31.7	8.7	46.4	66.5	34.3
CCSM4	-38.7	-7.1	1.9	-7.2	4.7	9.7	-22.2	-3.9	3.4	-43.4	5.7	10.3
CESM1-BGC	-18.2	13.8	20.8	-21.4	8	20.4	8.4	14.9	28.5	-31.3	13.9	23.5
CSIRO-Mk3-6-0	46.6	6.2	-2.2	16.8	-0.3	-35.9	27.6	4.2	-14.9	29.8	7.1	-15.3
GFDL-ESM2G	161.7	13.6	5.8	12.4	5.3	-2.7	-31.3	-7.7	-0.3	1.7	4.4	0.5
GFDL-ESM2M	6	6.9	4	-3.6	4	-3.1	-3.1	4.1	-2.4	-23	0.8	-10.7
HadGEM2-CC	-0.5	2.5	8.6	-10.1	0.7	-1	21.1	11.7	11.8	45.4	14.8	22.8
HadGEM2-ES	-1.7	-3.3	-9.2	-18.8	-1.8	-2.1	4.9	-0.5	1.4	35.1	16.7	15.8
inmcm4	-4.8	-8.7	-9.4	23.1	0.4	-12.5	-26.9	4.9	4	6.4	11.7	5.2
IPSL-CM5A-LR	65.6	36.3	8.4	167.5	35.5	19.3	107.3	54.8	44	145.8	101.9	76.5
IPSL-CM5A-MR	46.8	104.4	110.3	31.7	24	7	68.7	96.7	144.6	103.1	140.2	177.4
MIROC5	-14.5	6.4	15.4	-8	9.2	20.4	-9.2	15.3	36.9	-6	37.1	46.7
MIROC-ESM	-29.5	0.2	-0.7	-37.5	4.7	5.4	-35.7	11.2	15.1	-41.6	28.2	22.7
MPI-ESM-LR	10.9	-7.6	-6.3	-5.9	-9.3	-13	-11.3	-2	-2.4	-8.7	-5.8	-13.7
MPI-ESM-MR	17.1	1	-13.8	-8.8	6.2	-20	-10.3	1.5	-15.1	-19.7	1.1	-21
MRI-CGCM3	14.7	6.7	1.1	45.3	25.3	16.8	50.2	22.2	2.8	89.7	33.5	16.3
NorESM1-M	12.6	16.4	5.9	-19.2	5	5.9	-30.6	13.8	1.9	-14.9	19.1	4.5
Average	**15.6**	**12.2**	**8.4**	**8.6**	**10.0**	**8.4**	**8.5**	**16.6**	**2.8**	**17.8**	**29.1**	**15.3**

Seasonal rainfall totals: considering the seasonal changes of future rainfall, the result showed that the studied stations will have an increasing trend of *kiremt* rainfall totals (Table 18). Conditioned on the type of emission scenario and study station, *kiremt* rainfall will increase on average by 8.7-13.6 % in the 2050s and 3.1-32% in the 2080s. On the other hand, the magnitude of change in *kiremt* rainfall will have high spatial variation. Accordingly, Mekelle will see minimal increase in *kiremt* rainfall total both in the 2050s and 2080s particularly under the medium emission scenarios. Kiremt rainfall total at Kobo, Sirinka and Mekelle is expected to increase by 14.8-18.8%, 9.6-13.6% and 8.7-17.1%, respectively by the 2050s and by 11.4-32.1%, 5.6-25.5% and 3.1-24% by the 2080s varied with emission scenarios considered. Moreover, GCMs were not consistent in predicting the amount and direction of kiremt rainfall totals across the stations and emission scenarios. The result also indicated that kiremt rainfall total will be higher under the medium emission scenario than its counterpart. The increasing trend of *kiremt* rainfall of the studied stations of future climate might have a positive impact on crop production. However, this might be unfulfilled due to an increase in temperature that leads to an increase in evapotranspiration loss (Zeray *et al*., 2007; Conway and Schipper, 2011). In line with the present findings, the synthesis report produced by Agricultural Model Inter-compression and Improvement Project (AgMIP) reported an increase in mean seasonal rainfall (AgMIP, 2013).

Table 19. Projected changes (%) in *Kiremt* rainfall totals at Kobo, Srinka and Mekelle station

GCMs	RCP4.5 MID			RCP4.5 END			RCP8.5 MID			RCP8.5 END		
	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle	Kobo	Srinka	Mekelle
ACCESS1	-7.9	-9	-4	-6.5	-7	-1	1	-4.3	17.1	1	-8.7	6.4
bcc-csm1	-0.1	-8.7	-8.6	-5.3	-4.9	-5.8	1.6	-2.4	-1.7	12.8	14.9	12.7
BNU-ESM	35	29.5	26.9	55.3	46.9	41.8	43.4	26.6	20.8	62.3	58	51.6
CanESM2	18.8	14.3	12.4	23.4	14.6	13.5	24.5	10.2	7.6	58.4	39.1	30.4
CCSM4	-1.7	-0.2	6.1	9.7	4.7	12.8	1.4	-0.5	6.6	-1.1	13.3	18.4
CESM1-BGC	12.4	19.4	27.5	3.3	11.4	27.1	12.8	11.6	34.8	4.3	22.8	33.3
CSIRO-Mk3-6-0	-6.1	-26.3	-8.9	-11.6	-31.7	-41.8	-7.4	-25.1	-16.3	-7.7	-26.9	-15.4
GFDL-ESM2G	71.7	6	3.6	3.3	2	-1.5	-4.5	5.5	6.7	3.4	3.2	2.9
GFDL-ESM2M	8.3	5.9	-0.3	4.1	3.7	-5	3.7	0.1	-4.8	2.9	2.3	-12.6
HadGEM2-CC	3	-0.1	10.6	-2.2	-0.4	1.5	10.8	-2.2	10.7	14.2	-2.6	19.3
HadGEM2-ES	-4.7	-10.5	-9.3	-2.8	-7.4	0.6	-0.8	-9.3	1.3	12.9	-5.8	13.6
inmcm4	-7.2	-5.9	-8.6	-4.8	-6.7	-16.7	3.7	12.1	9.1	12	18.9	6.6
IPSL-CM5A-LR	52.3	12.1	6.7	103	19.1	19.6	96.2	43.7	43.1	171.8	79.2	72.9
IPSL-CM5A-MR	101.9	141.2	123.2	21.5	14.4	0.9	118.9	126.2	154.3	153.3	197.2	189.4
MIROC5	9	22	20.5	12.3	27.2	25.5	19.9	38	44.2	41.4	64.8	52.8
MIROC-ESM	2	4.5	2.8	6.6	12.3	11.6	14.4	21.7	21.2	29.5	33.7	30.7
MPI-ESM-LR	-7.2	-15.3	-15.2	-8.7	-16.2	-20.8	-2.6	-4.8	-4.5	-3.8	-8.6	-26.1
MPI-ESM-MR	0.3	-1	-17.4	1.9	-2.6	-21.5	-0.2	1.7	-18	1.1	-2.3	-26.3
MRI-CGCM3	5.6	5.9	0.1	22.6	22	14.9	19.4	11.8	-1.4	26.4	3.8	7.8
NorESM1-M	10.2	8.3	6.7	3.5	9.8	6	2	12	10.8	15.7	13.4	11.9
Average	**14.8**	**9.6**	**8.7**	**11.4**	**5.6**	**3.1**	**18.8**	**13.6**	**17.1**	**32.1**	**25.5**	**24**

4.1.3.2. Projected temperature change

Table 19 shows the predicted changes of temperature at different stations in northern Ethiopia. The result revealed that the stations will get warmer than today, but the magnitude of change may depend on location of the station and concentration pathways considered. On average, maximum temperature will increase by 1.8 ^{o}C and 2.2 ^{o}C, for 2050s and 2080s respectively under the medium emission scenario; and 2.4 ^{o}C and 3.8 ^{o}C for the same period under the highest emission scenario. Likewise, minimum temperature will increase on average by 1.8 ^{o}C and 2.4 ^{o}C under the medium emission scenario and by 2.7 ^{o}C and 4.7 ^{o}C under the highest emission scenario by the 2050s and 2080s respectively. The result also revealed that for most stations, the magnitude of temperature change will be higher under the highest emission scenario than its counterpart. The result further revealed that temperature of the studied stations would increase with time and the warming is expected to be more for minimum temperature. In general, future temperature is expected to increase consistently at the stations considered.

Table 20. Projected temperature changes (^{o}C) in northern Ethiopia using an average outputs of 20GCM models for two representative concentration pathways

Station name	Maximum temperature change (^{0}C)				Minimum temperatures change (^{0}C)			
	2050s		2080s		2050s		2080s	
	RCPs 4.5	RCPs 8.5	RCPs 4.5	RCPs 8.5	RCPs 4.5	RCPs 8.5	RCPs 4.5	RCPs 8.5
Mekelle	1.7	2.4	2.2	4.0	1.8	2.7	2.3	4.6
Kobo	1.8	2.3	2.1	4.0	1.7	2.7	2.4	4.7
Sirinka	1.8	2.4	2.3	3.4	1.8	2.8	2.4	4.7
Average	1.8	2.4	2.2	3.8	1.8	2.7	2.4	4.7

Projected annual and seasonal temperature changes, as compared to the base period, are presented in Table 18. The results revealed that mean annual temperature will increase by the 2050s and 2080s in all stations under medium and highest emission scenarios. Similarly, mean temperature during *Kiremt and Belg* seasons will increase in all stations for mid and end time periods under the prescribed emission scenarios. On the other hand, mean temperature increase during *Belg* season particularly at Mekelle and Kobo will be higher as compared to the mean annual and *Kiremt* temperature under both emission scenarios.

The result is in line with NAPA (2007), Zeray *et al*. (2007), Conway and Schipper (2011), Setegn *et al*. (2011), and Ayalew *et al*. (2012) that reported an increase in minimum and maximum temperature in Ethiopia in the coming decades.

Table 21. Projected mean annual, kiremt, and belg temperature (°c) changes as compared to baseline period under RCP4.5 and RCP8.5 emission scenarios in northern Ethiopia

Station	RCPs	Period	Belg	Kiremt	Annual
Mekelle	4.5	MID	1.9	1.8	1.8
		END	2.5	2.3	2.3
	8.5	MID	2.7	2.5	2.6
		END	4.5	4.3	4.3
Kobo	4.5	MID	1.9	1.8	1.8
		END	2.5	2.2	2.3
	8.5	MID	2.6	2.4	2.5
		END	4.5	4.2	4.4
Sirinka	4.5	MID	1.8	1.8	1.8
		END	2.2	2.3	2.4
	8.5	MID	2.5	2.5	2.6
		END	3.9	4.0	4.1

4.2. Model Calibration and Evaluation

4.2.1. Model Calibration

Table 21 shows measured and simulated values and overall model performance indicators on sorghum and wheat crops at the study area. The result indicated that the CERES-sorghum model fairly simulated the observed values of both varieties during model calibration period. However, the variability observed in ‘Melkam’ was explained more by the model than its counterpart. According to the estimated value, the root mean square error (RMSE), which is an overall measure of the model performance showed a good fit (or the lower the values of RMSE, the better the model to explain the variation of the data set) of the model for sorghum cultivars (Teshale and Melkam). The index of agreement (d-static) also reveals a good fit of the model to explain variabilities related to days to anthesis, days to maturity and grain yield for both sorghum cultivars. Similarly, during model calibration, the result showed good performance of the CERES-wheat model in simulating days to anthesis, days to maturity and yield of the crop. The statistical indicators used to indicate model performance lied within an acceptable range. The model verification test using RMSEn for both crops also showed within a possible range that indicated the model is well adjusted with site specific data’s.

Table 22. Comparison of simulated and observed days to anthesis, maturity and grain yield of Sorghum and Wheat during model calibration at Kobo and Mekelle, respectively

Crop type	Variety	Variable	Mean		R^2	RMSE	RMSEn	d-Stat.
			Observed	**Simulated**				
Sorghum	Teshale	Anthesis day	73	73	0.79	0.8	1.1	0.92
		Yield (kg/ha)	2809	2688	0.61	289.4	10.3	0..84
		Maturity day	111	110	0.92	1.4	1.2	0.85
	Melkam	Anthesis day	81	81	1.0	0.82	1.0	0.96
		Yield (kg/ha)	2504	2021	0.96	520.1	20.7	0.87
		Maturity day	110	109	0.97	1.3	1.2	0.92
Wheat	Mekele-1	Anthesis day	64	65	0.57	1	1.6	0.68
		Yield (kg/ha)	2848	2636	0.74	435.7	15.3	0.74
		Maturity day	104	105	0.89	1.3	1.2	0.69

4.2.2. Model validation

Comparison between simulated and observed days to anthesis, maturity and grain yield of sorghum and wheat crops during model validation is depicted in Table 22 and figures 6-8. The result showed that there was strong agreement between the simulated and observed datasets of both crops. The index of agreement, coefficient of determination and root mean square value revealed that the CERES-Sorghum and CERES-Wheat models are well-adjusted and showed a good agreement between observed and simulated parameters of both crops during calibration. The statistical indicators revealed that as compared to calibration period, the observed parameters were simulated better during validation period. Therefore, the models could be used to simulate growth and development of the two crops.

Table 23 Model performance indicator statistical output for Model validation for Sorghum and wheat crop variety

Crop type	Variety	Variable	Mean		r-Square	RMSE	d-Stat.
			Observed	**Simulated**			
Sorghum	Teshale	Anthesis day	73	73	0.79	0.82	0.92
		Yield kg/ha	2809	2688	0.62	289.4	0.85
		Maturity day	111	110	0.92	1.4	0.86
	Melkam	Anthesis day	81	81	1	0.82	0.95
		Yield kg/ha	2504	2021	0.96	520.1	0.87
		Maturity day	110	109	0.97	1.3	0.92
Wheat	Mekele-1	Anthesis day	65	66	0.81	0.86	0.80
		Yield kg/ha	2220	2007	0.80	305.6	0.79
		Maturity day	106	106	0.88	2.8	0.77

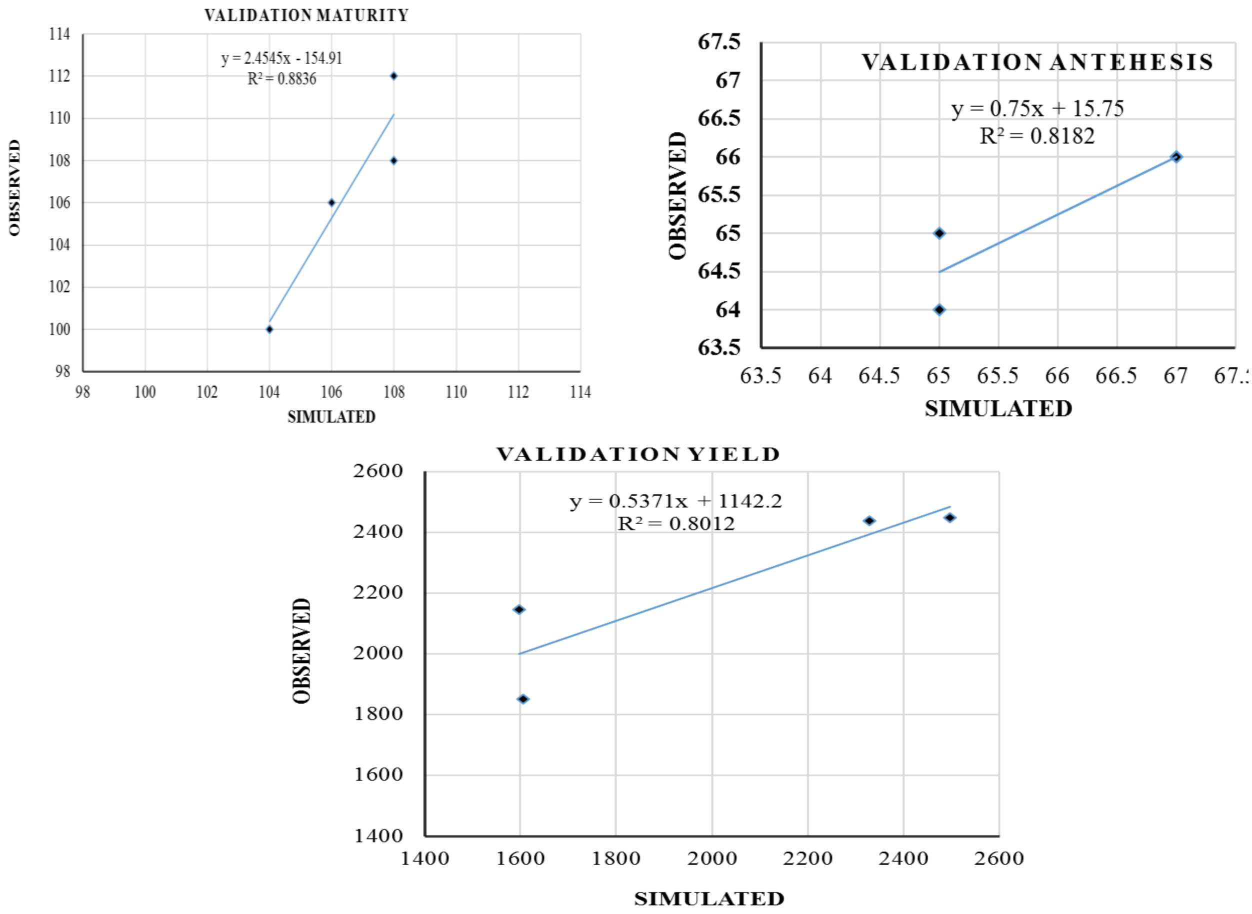

Figure 7: Relationship between simulated anthesis, maturity and final grain yield of wheat at Mekelle

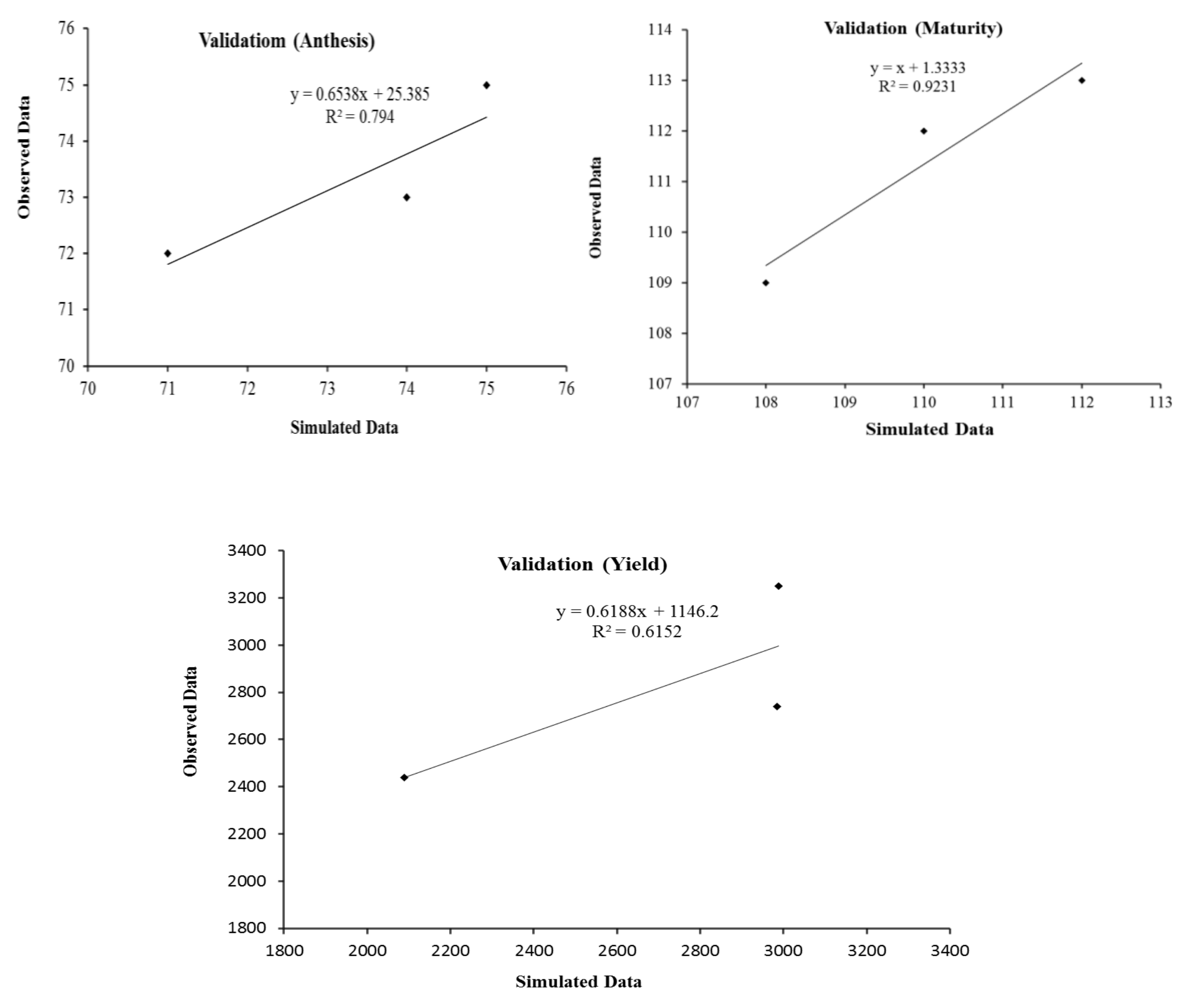

Figure 8: Relationship between simulated and observed values of anthesis, maturity and final grain yield for sorghum (Teshale) at Kobo

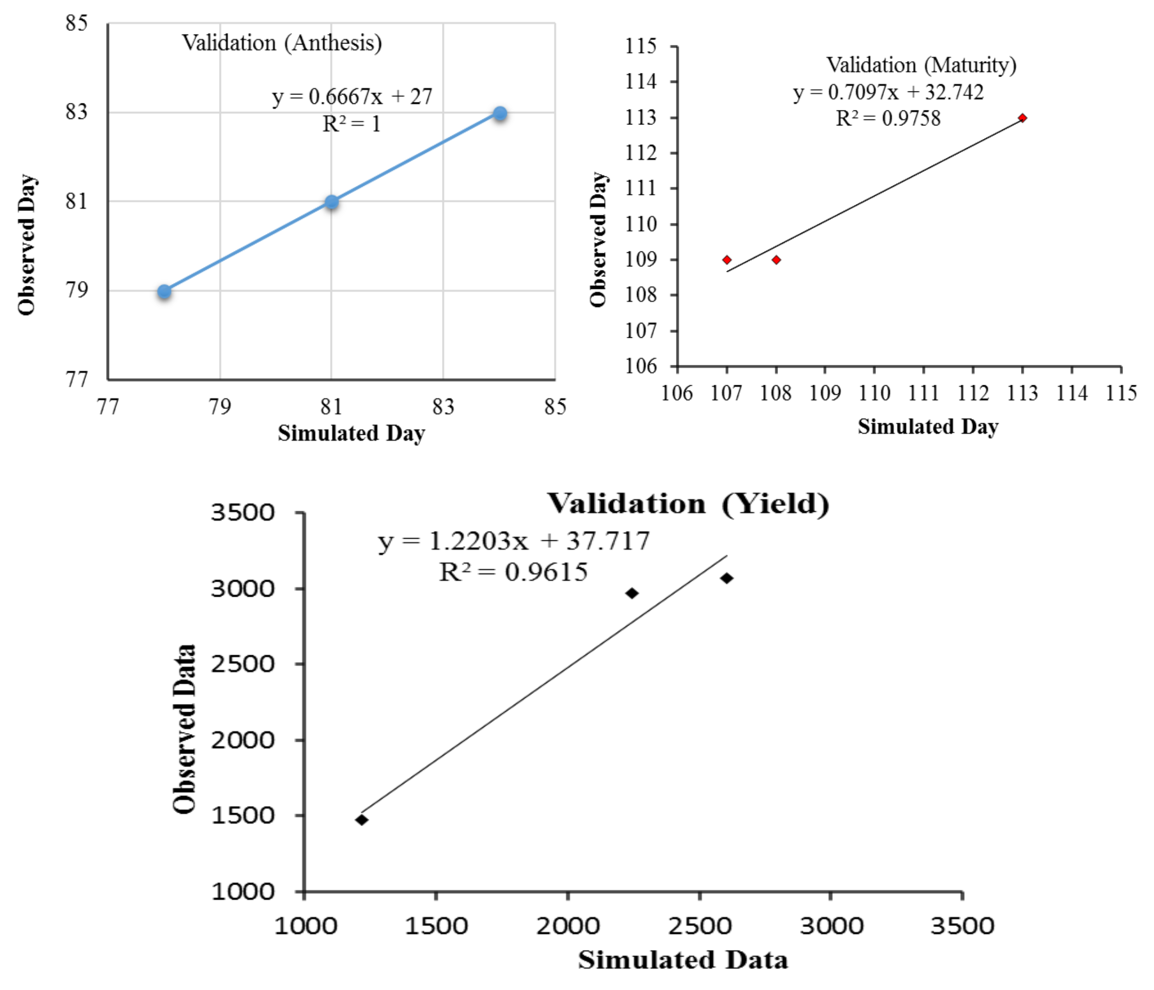

Figure 9: Relationship between simulated and observed values of anthesis, maturity and final grain yield for sorghum (Melkam) at Kobo

4.3. Crop response to future climate

4.3.1. Impact of future climate on sorghum production

The impact of projected future climate on yield for two sorghum cultivars depicted at Table 23. The overall result showed a general tendency of decreasing yield of sorghum. The simulated yield of sorghum is varied with the type of climate models employed and emission scenarios used. However, on average, sorghum yield is expected to decrease by 1.2-23% accordingly with emission scenarios, period of analysis, variety and the study location. Based on growing location, sorghum production is more affected due to future climatic conditions at Kobo relative to Sirinka. Similarly, differences were observed among varieties of sorghum for future climate. In this regard, Teshale would be affected more due to future climate change than its counterpart (Melkam). Yield of sorghum under the projected future climate would be varied also with emission scenarios (RCP's) assumed to project the future climate change scenario. Inline of this, yield of both sorghum cultivars will be expected to decrease under the highest emission scenario in both growing locations. Likewise, regardless of location, variety and emission scenarios, productivity of sorghum will be deceased drastically towards the end of the century (2080s) compared to mid-century (2050s).

In general, the investigation of future sorghum production using the projected climate change scenarios showed a reduction in yield. The consistent increase in projected temperature and variable rainfall may contributed for the predicted yield reduction in the study areas. Increasing temperature which accelerates growth and development of plants leading to less time for carbon assimilation and biomass accumulation before seed set and causing for less yield (Rawson, 1992; Marison, 1996). Moreover, increase in temperature would increase the evapotranspiration demand of the atmosphere and hence creates moisture deficit in the root zone, which in turn leads to yield reduction. This will have a far reaching effect on the livelihood of the community who depend on sorghum production for food, feed, fuel and construction materials. Therefore, it might be critical to adapt in situ moisture conservation and utilization practices as well as envisaging sorghum breeding strategies that target to develop heat tolerant varieties to improve and sustain the productivity of sorghum in the study area.

Table 24 Future yield change (%) for sorghum at Kobo and Sirinka for Mid (2040-2069) and End (2070-2099) century under RCP4.5 and RCP8.5 relative to the bassline yield

	Kobo								Sirinka							
	Melkam				Teshale				Melkam				Teshale			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
GCM	MID	END	MID	END	MID	END	MID	END	MID	END	MID	END	MID	END	MID	END
ACCESS-0	-6.0	-10.2	-8.0	-23.5	-7.9	-13.1	-11.2	-34.1	-0.7	-3.3	3.7	-14.6	-3.4	-6.3	-1.4	-21.1
bcc-csm1	-3.5	-1.7	-2.8	-10.3	-4.4	-4.8	-6.3	-15.8	0.5	0.2	6.6	-7.9	-1.8	-2.5	2.6	-13.5
BNU-ESM	7.0	8.0	1.5	4.0	3.0	2.4	-4.3	-4.5	7.4	8.8	16.4	12.3	3.9	5.4	14.3	8.3
CanESM2	-1.2	-2.6	-4.2	-15.4	-5.3	-6.9	-9.9	-25.5	-3.1	-5.2	-2.1	-25.2	-7.4	-9.6	-7.8	-32.4
CCSM4	2.9	2.1	0.9	-5.1	-0.6	-2.0	-3.4	-10.7	1.8	2.1	7.7	-5.2	-1.1	-1.5	4.3	-10.1
CESM!-BGC	3.0	2.5	0.9	-3.9	-2.1	-2.2	-3.4	-9.7	3.9	2.9	9.0	-4.2	0.1	-0.5	5.0	-9.7
CSIRO_Mk3-6-0	-11.3	-14.5	-10.1	-27.1	-10.1	-14.3	-11.0	-37.2	-6.1	-9.5	0.5	-20.2	-7.2	-10.3	-2.9	-27.1
GFDL-ESM2G	8.0	2.3	-0.7	-8.8	5.2	2.7	-5.0	-13.1	-1.3	-3.3	-0.6	-28.9	2.0	1.5	7.2	-23.8
GFDL-ESM2M	0.8	-1.5	-2.8	-10.7	-2.9	-4.5	-6.4	-15.0	2.6	1.8	7.3	-5.6	0.2	-1.6	3.4	-10.1
HadGEM2-CC	-3.6	-8.4	-9.6	-24.5	-6.4	-11.8	-13.2	-37.7	-0.5	-3.2	2.1	-17.8	-3.9	-7.3	-3.2	-28.8
HadGEM2-ES	-7.5	-10.4	-10.1	-24.5	-9.0	-14.7	-14.1	-37.7	-2.6	-5.6	1.5	-21.3	-5.2	-9.8	-4.0	-31.6
inmcm4	-1.7	-2.9	0.1	-5.9	-3.1	-5.2	-4.8	-12.6	0.6	0.7	4.6	-7.5	-1.2	-1.6	1.1	-12.7
IPSL-CM5A-LR	-1.3	-4.9	-8.3	-29.9	-9.6	-15.4	-20.7	-44.0	2.6	1.5	5.7	-15.5	-1.2	-2.7	-0.6	-24.3
IPSL-CM5A-MR	-8.0	-11.3	-14.8	-34.2	-20.8	-15.7	-28.3	-49.3	0.7	-2.7	0.2	-21.4	-5.8	-7.0	-7.1	-30.5
MIROC5	3.4	2.2	2.4	-3.0	-1.3	-3.7	-4.6	-13.1	4.3	3.9	11.0	-0.8	0.7	-0.8	6.6	-6.5
MIROC5-ESM	0.5	2.7	3.4	-4.8	-1.6	-1.3	-2.0	-13.8	1.8	2.3	10.0	-1.7	-1.1	-2.0	6.7	-6.8
MPI-ESM-LR	-4.8	-7.8	-6.8	-22.0	-6.3	-8.6	-10.4	-31.1	-1.2	-2.2	4.3	-13.6	-3.2	-4.9	-0.1	-20.4
MPI-ESM-MR	-3.3	-4.6	-6.6	-19.6	-6.3	-8.3	-9.9	-28.0	0.6	-1.1	5.6	-12.8	-2.5	-4.3	0.6	-19.5
MRI-CGCM3	-1.0	1.2	-0.9	-9.8	-3.0	-4.2	-6.2	-14.2	2.1	2.4	7.4	-11.1	-1.0	-1.9	3.3	-15.1
NorESM1-M	2.7	2.5	1.2	-2.0	-0.5	-1.9	-3.0	-8.1	2.6	2.7	9.4	-3.4	0.2	-0.8	5.4	-8.1
Mean	**-1.2**	**-2.9**	**-3.8**	**-14.0**	**-4.6**	**-6.7**	**-8.9**	**-22.8**	**0.8**	**-0.3**	**5.5**	**-11.3**	**-1.9**	**-3.4**	**1.7**	**-17.2**

4.3.2. Impact of future climate on wheat production

The impact of future climate change on production of wheat at Mekelle under different climate models, emission scenarios and period of analysis is depicted in Table 24. The result revealed that wheat yield under future climate would differ for different climate models. For instance, wheat yield would decrease under future climate as predicted by BNU-ESM, CanESM2, CESM1-BGC and MIROC5 climate models and under both emission scenarios. Whereas, a maximum decline of yield for wheat is expected under IPSL-CM5A-MR climate model accordingly varied with emission scenarios and periods considered. However, on average wheat yield is expected to increase by 2.2-6.6% conditioned on emission scenarios considered by the 2050s while yield might decline to -2.3% by the end of the century under the highest emission scenario.

According to Asseng *et al*. (2011), wheat is a cool season crop and increasing temperature shorten its growth period by accelerating phenological development, resulting in reduced yield but Liu et al. (2008) underlined that increase in temperature could reduce wheat yield when the seasonal growing temperature is above the optimum wheat growing temperature (15-20^{o}C) of the locality. According to the recent report of IPCC, the highest maximum and minimum temperature is projected under RCP8.5 for 2070-2099 and this seriously reduce crop yield especially when it coincides with the reproductive stage of the crop. Whereas, the observed long term climate data from the nearby station shows, the mean seasonal *(Kiremt)* temperature of the area ranges from 15.1 to 17^{o}C. Through this, small increase of wheat yield at the study site might arise from this assumption and the projected decline of yield for RCP8.5 in the end of the century is due to maximum projection of seasonal temperature by 4.3^{o}C.

Table 25: Simulated yield change of (Mekele-I) Enderta for Mid (2040-2069) and End (2070-2099) of the century under RCP4.5 and RCP8.5 relative to the base period

GCM	Mekelle			
	Wheat (Mekele-1)			
	RCP4.5		RCP8.5	
	MID	END	MID	END
ACCESS-0	9.7	10.4	5.1	-1.2
bcc-csm1	14.2	19.8	19.5	7.0
BNU-ESM	-12.4	-14.7	-0.8	-16.3
CanESM2	-1.2	5.0	9.7	-5.4
CCSM4	1.6	5.0	10.4	4.0
CESM!-BGC	-10.6	-4.3	-8.2	-6.0
CSIRO_Mk3-6-0	12.2	20.6	28.2	4.1
GFDL-ESM2G	3.5	16.4	11.2	15.7
GFDL-ESM2M	7.6	18.9	22.4	20.2
HadGEM2-CC	0.2	8.9	9.1	-5.9
HadGEM2-ES	8.4	5.2	13.7	-5.8
inmcm4	13.9	28.1	8.4	10.9
IPSL-CM5A-LR	3.3	2.4	-11.4	-25.1
IPSL-CM5A-MR	-44	4.5	-44.6	-55.6
MIROC5	-8.2	-3.5	-14	-16.8
MIROC5-ESM	3	4.8	-2	-5.3
MPI-ESM-LR	17.2	22.1	21.8	7.2
MPI-ESM-MR	17.5	22.5	28.6	10.4
MRI-CGCM3	7.2	4.8	18.2	9.9
NorESM1-M	0.8	10.3	6.5	7.9
Average	**2.2**	**9.4**	**6.6**	**-2.3**

4.3.3. Impacts of climate change on wheat vs sorghum crops

Comparison of climate change impacts between the yield of wheat (C3 crop) and sorghum (C4 crop) is depicted in Figure 8. The result revealed that projected yield of both sorgum and wheat adversly affected by future climate acording to the projected climate change scenarios of the studied sites. The impact of projected climate on both crops varied with emission scenarios, period of analysis and study sites considered. Accordingly, the productivity of sorghum will be negatively affected in future climate under both emission scenarios by the 2050s and 2080s. Nevertheless, the effect of climate change on sorghum yield is less by 2050s under medium emission scenario assumption compared with 2080s with higher emission scenario. Yield of wheat would increase in the future under the medium emission scenario and expected to decrease under the highest emission scenario at the end of the century. Most studies also showed elevated CO_2 can affect the production system through stimulation of photosynthesis and water use efficiency for wheat and sorghum plants but sorghum is least benefited from photosynthesis from elevated CO_2.

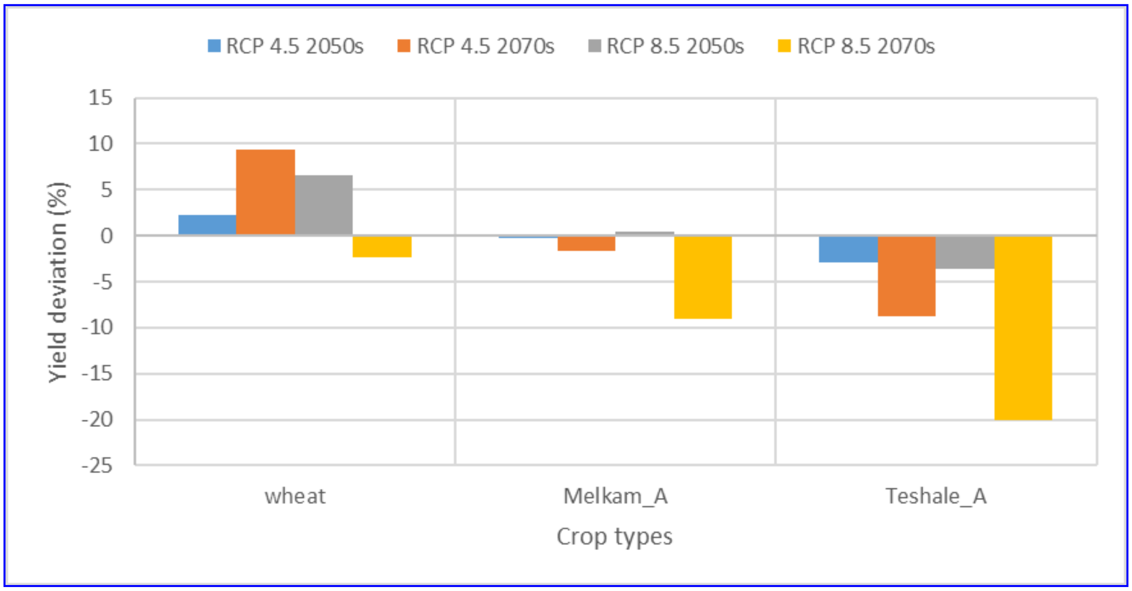

Figure 10. comparison of yield change for wheat and sorghum crops under the future climate

4.4. Sensitivity of Sorghum and Wheat Yields for Climate Variabilities

Sorghum and wheat yield response for a change in temperature, precipitation and atmospheric CO2 from the base period is presented at Table 25. The result showed that sensitivity of sorghum yield to climate variability and change varied with variety and study sites. In this regard, Teshale is highly sensitive to a change in temperature from the baseline climate at Kobo and Sirinka. On the other hand, regardless of rainfall variation, rise in temperature by 2 ^{o}C and 3 ^{o}C would result an increase of yield for Melkam variety. The yield response of the two varieties decreased with increase in temperature. Particularly, yield of melkam will be negatively affected when the temperature rises above 3^{o}C. Nonetheless, melkam variety showed an increase of yield for a change in temperature by more than 3^{o}C and combined with high concentration of CO_2 (750ppm) and an increase of rainfall by 10%.

The sensitivity result for wheat revealed that increasing of temperature is declined yield at Mekelle. The diverse response of sorghum and wheat crops/cultivars to a similar change in temperature might arised from different temperature requirements among cultivars or crops (Rotters and Geijin, 1999) and a degree day concept where can be used as a crop development stage and a cultivar specific descriptor. The result of sensitivity analysis for a combination of temperature and rainfall for sorghum and wheat showed almost similar response as a temperature change. However, the rise of atmospheric CO_2 by 540 and 750ppm from the current level would result in increase of yield by 4.5 to 6.9% for sorghum. Temperature and rainfall changes would not contribute significantly for sorghum yield during testing the combined effects under a constant atmospheric CO_2 level. Further, the rising of atmospheric CO_2 to 750 ppm with higher temperature and a decline of rainfall by 10% would result in an increase of wheat yield by 25.7%. Similar studies undertaken by International Maize and Wheat Improvement Center (CIMMYT) showed that a little decline or rise of yield by 2050s partly due to CO2 effect and combination of higher temperatures with constant or increases in rainfall in Ethiopia (Sharma *et al*., 2015).

Table 26. Sensitivity test for sorghum and wheat yield responses for a change in temperature, rainfall, atmospheric CO2 and the combined at Kobo, Sirinka and Mekelle.

Climate change	Sorghum				Wheat
	Kobo		Sirinka		Mekelle
	Teshale	Melkam	Teshale	Melkam	Mekele-1
Base+2ºC	-13.0	4.5	-13.9	13.7	-6.4
Base+3ºC	-23.4	2.3	-25.2	8.4	-13.7
Base+4.5ºC	-38.9	-10.6	-40.9	-6.6	-25.5
Base+2ºC+10%RF	-12.8	5.9	-13.4	15.4	-9.3
Base+3ºC+10%RF	-23.6	3.3	-25.7	9.2	-15.5
Base+4.5ºC+10%RF	-38.9	-10.1	-41.3	-6.8	-26.4
Base+2ºC-10%RF	-13.4	2.9	-14.8	11.3	-4.4
Base+3ºC-10%RF	-23.5	0.3	-25.3	6.9	-12.5
Base+4.5ºC-10%RF	-39.1	-12.0	-40.5	-7.2	-24.8
Base+2ºC+10%RF+540ppm	-8.6	6.9	-5.6	17.2	-0.5
Base+3ºC+10%RF+540ppm	-19.1	5.7	-18.4	14.0	-5.2
Base+4.5ºC+10%RF+540ppm	-34.2	-6.4	-35.2	-0.1	-15.4
Base+2ºC+10%RF+540ppm	-9.0	4.6	-6.0	13.6	7.9
Base+3ºC+10%RF+540ppm	-19.0	3.0	-17.7	11.9	0.8
Base+4.5ºC+10%RF+540ppm	-34.3	-8.3	-34.4	-0.1	-12.2
Base+2ºC+10%RF+750ppm	-6.6	8.7	-1.5	17.8	3.8
Base+3ºC+10%RF+750ppm	-17.1	7.4	-14.6	16.3	1.8
Base+4.5ºC+10%RF+750ppm	-32.4	-4.6	-31.9	3.1	-5.6
Base+2ºC+10%RF+750ppm	-6.9	6.2	-1.6	14.8	16.5
Base+3ºC+10%RF+750ppm	-17.0	5.1	-13.7	14.4	12
Base+4.5ºC+10%RF+750ppm	-32.4	-6.3	-31.0	3.2	0.2

4.5. Evaluation of Adaptation Practices for Sorghum and Wheat Production

4.5.1. Planting Date

Adapting planting date is one of the strategy to reduce the negative impacts of the changed climate (White *et al*., 2011) on wheat and sorghum yield. Table 26 presents the yield response of sorghum and wheat to different planting windows. The result revealed that, regardless of emission scenarios and period of study, early planting (16-30 June) would give a better yield for both sorghum varieties at Kobo and Sirinka. However, delaying the planting dates beyond the normal would result in reduction of yield for both varieties at Kobo and Sirinka. On the other hand, early and late planting date at Mekelle would result yield penalty. However, normal planting date (01-15 July) is suggested for future production of wheat to cope the adverse impacts of climate change. The numbers in bracket shows devotion in yield in percent from the baseline yield.

Table 27 sorghum and wheat yield response for early, normal and late planting date at Kobo, Sirinka and Mekelle under RCP4.5 and RCP8.5 using DSSAT

Districts	Cultivar	Planting date	Simulated Yield (Yield Deviation %)			
			RCP4.5		RCP8.5	
			MID	END	MID	END
Kobo	Melkam	Early	3333.9 **(15.9)**	3287.3 **(14.2)**	3249.6 **(13.1)**	2852.3 **(7.1)**
		Normal	3065.2 **(6.6)**	3067.4 **(6.6)**	3073.9 **(7.0)**	2477.1 **(-7.0)**
		Late	2543.9 **(-11.5)**	2559.7 **(-11.1)**	2605.6 **(-9.3)**	2038.4 **(-23.5)**
	Baseline Yield		2876.0	2878.8	2873.3	2663.6
	Teshale	Early	3325.7 (**4.7**)	3204.7 (**4.2**)	3102.7 (**2.3**)	2495.3 (**-0.2**)
		Normal	3300.5 (**4.0**)	3191.8 (**3.8**)	3132.1 (**3.3**)	2551.7 (**2.0**)
		Late	2972.3 **(-6.4)**	2924.6 **(-4.9)**	2941.8 **(-3.0)**	2513.4 **(0.5)**
	Baseline Yield		**3175.0**	**3075.7**	**3032.1**	**2501.4**
Sirinka	Melkam	Early	4434.1 (**11.4**)	4392.3 (**32.9**)	4387.5 (**11.2**)	3761.0 (**8.0**)
		Normal	4273.6 (**7.4**)	3982.5 (**22.6**)	4172.6 (**5.7**)	3545.6 (**1.8**)
		Late	3331.8 (**-16.3**)	3336.5 (**6.4**)	3665.9 (**7.1**)	3185.0 (**-8.5**)
	Baseline Yield		**3980.8**	**3982.6**	**3946.7**	**3482.0**
	Teshale	Early	4337.0 (**10.8**)	4108.7 (**10.8**)	4331.4 (**4.0**)	3099.1 (**12.5**)
		Normal	3957.1 (**1.1**)	3743.6 (**1.0**)	4566.6 (**9.7**)	2733.3 (**-0.8**)
		Late	3394.4 (**-13.3**)	3282.7 (**-11.5**)	4254.9 (**2.2**)	2604.9 (**-5.5**)
	Baseline Yield		**3914.6**	**3708.1**	**4163.4**	**2755.1**
Mekelle	Mekele-1	Early	1970.7 (**-2.2**)	2024.0 **(-6.1)**	2110.4 **(0.4)**	1845.9 **(-4.1)**
		Normal	2052.1 (**1.9**)	2137.7 **(-0.8)**	1735.0 **(-17.4)**	1905.1 **(-1.1)**
		Late	1598.0 **(-20.7)**	1771.8 **(-17.8)**	1414.1 **(-32.1)**	1718.5 **(-10.8)**
	Baseline Yield		**2014.5**	**2155.7**	**2101.2**	**1925.7**

4.5.2. Fertilizer Application Rate

The response of yield to nitrogen fertilizer application for future climate showed an increase in yield for sorghum and wheat. Comparison of future and current yield responses of wheat and sorghum crops for different fertilization rates under projected future climate is portrayed in Figure 10. The result indicated that increasing of N fertilization rate would result in increased yield of both sorghum cultivars by 2050s and 2080s at Kobo and Sirinka. Applying 73 kg/ha of nitrogen fertilizer rate would result a decline in yield by 2080s for Teshale sorghum variety under both emission scenarios at the studied sites. In line with this, application of 73kg/ha of nitrogen would result a decline in yield for melkam variety by 2050s at Kobo and an increase of yield at Sirinka relative to 2080s.

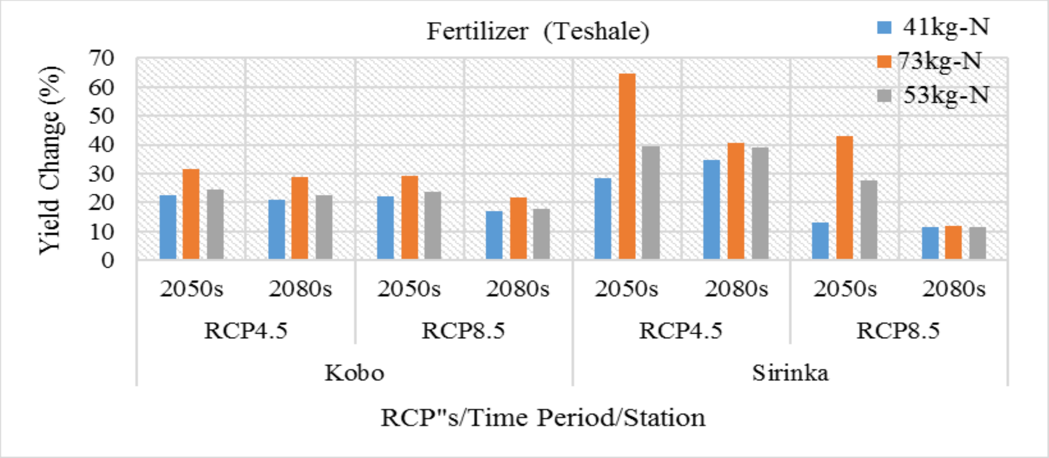

Figure 11. Yield response of sorghum (Teshale variety) for different fertilizer application rates under future climate conditions at Kobo and Sirinka

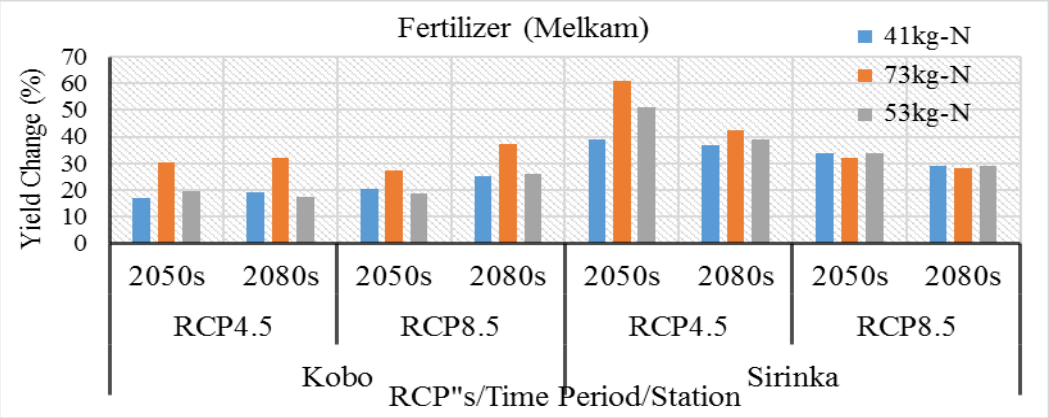

Figure 12. Yield response of sorghum (Melkam variety) for different fertilizer application rates by 2050s and 2080s under different emission scenarios at Kobo and Sirinka

Similarly, the simulated output indicated that increasing nitrogen fertilizer rates gives a higher yield of wheat at Enderta study site. In this regard, application of 73kg/ha of nitrogen fertilizer would result a higher yield of wheat by 2050s than 2080s under both emission scenarios. In general, the model indicated that, increasing fertilization rate would play a significant role in maintaining or increasing yield under future climate conditions.

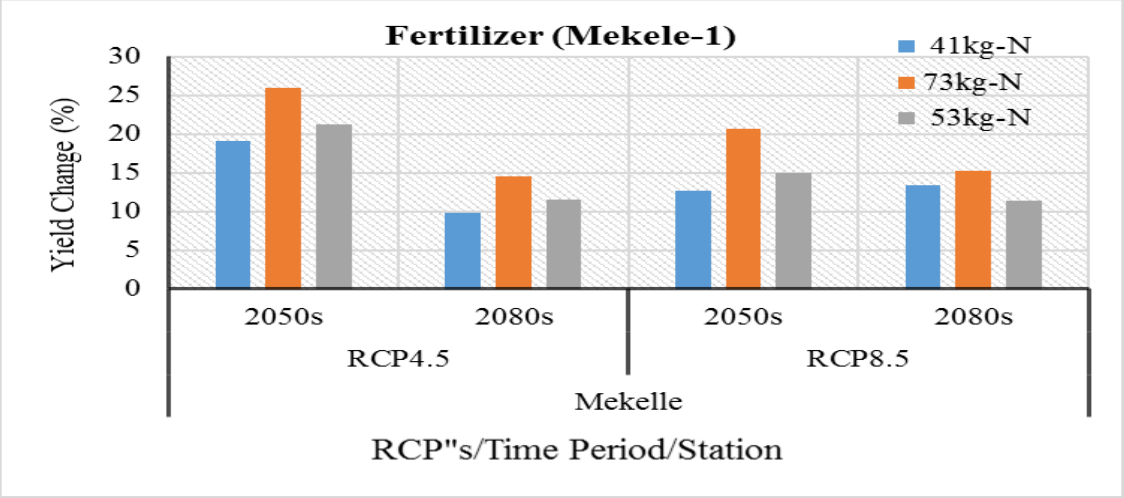

Figure 13. Yield response of wheat (Mekele-1) for different fertilizer application rates by 2050s and 2080s under different emission scenarios at Enderta

4.5.3. Plant Population (Planting Density)

Adjusted plant population to available resources, particularly soil water and nutrient level were used to improve water-use efficiency of crops in dryland areas (Kidane *et al*., 2004). The simulated results from CERES-Sorghum and CERES-wheat crop models indicated that increasing plant population gives a better yield for both crops. The maximum yield change for sorghum and wheat cultivars were simulated using 9 plants/m^2 and 300 plants/m^2 respectively from 2070-2099 under RCP8.5. Previous studies undertaken in northern Ethiopia showed that plant population from 6plants/m^2 to 9 plants/m^2 would result an increasing yield for sorghum based on seasonal rainfall distribution of the locality. Plant populations greater than necessary would reduce the plants' ability to cope with moisture stress and produce plants with smaller stems which are more susceptible to lodging.

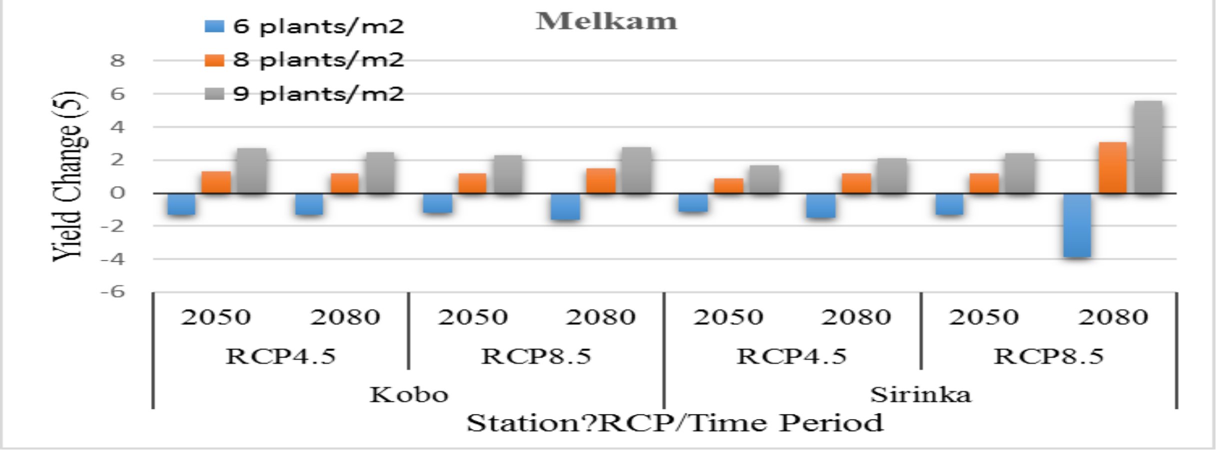

Figure 14. Sorghum (melkam) yield response for plant population under future climate for RCP4.5 and RCP8.5

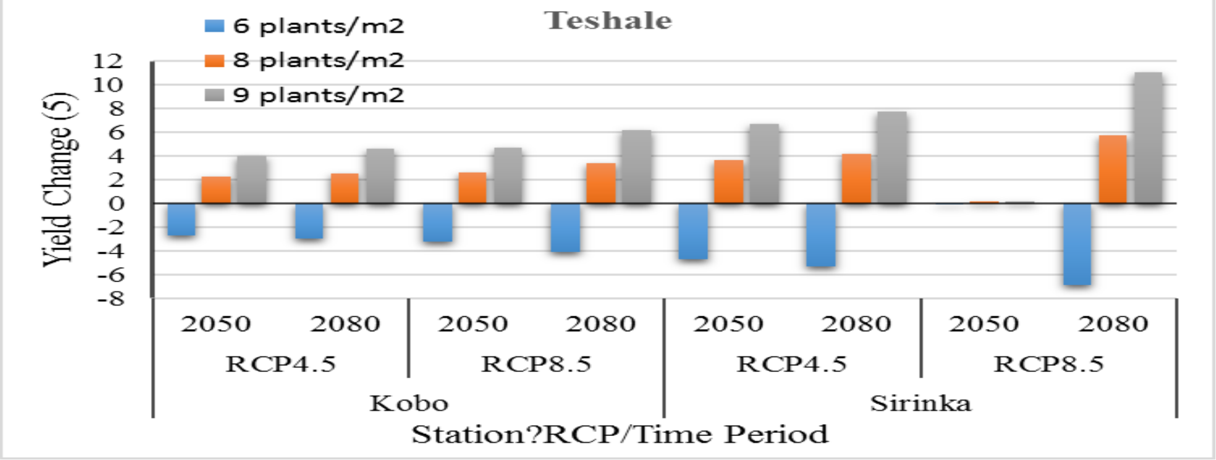

Figure 15. Sorghum (Teshale) yield response for plant population under future climate for RCP4.5 and RCP8.5

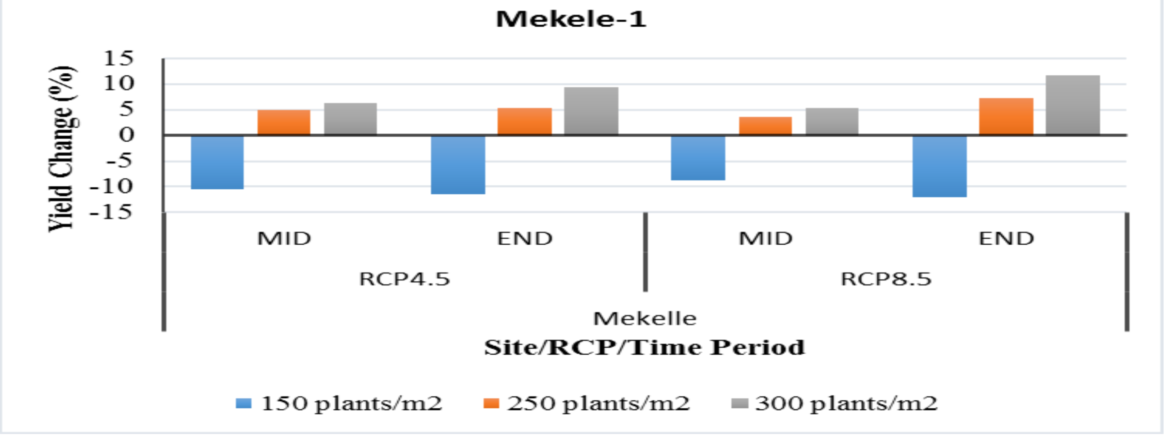

Figure 16. Wheat (mekele-1) yield response for plant population under future climate for RCP4.5 and RCP8.5

5. SUMMARY, CONCLUSION AND RECOMMENDATION

5.1. Summary and Conclusion

Recently, due to concern over the potential impacts of greenhouse gases in the atmosphere, the issue of climate change has moved to the forefront of the global scientific agenda. Ethiopia is arguably the most at risk nation from climate change impacts on agricultural productivity and food security. In view of this, this study was conducted to assess the impact of climate change on yield of wheat and sorghum, and to identify a crop management practices that could increase the yield of the two crops under future climate. This study was focused in three sites (Kobo, Sirinka and Mekelle) representing two agro-ecologies (mainly lowland and mid-highland) and two production systems (wheat and sorghum). Long term climate data of the respective sites were analyzed to characterize the area. In addition, future climate of each site was downscaled using AgMIP climate scenario generation scripts for 20-global climate models. The cropping system model, DSSAT4.6, was used to assess impact of future climate change on yield of sorghum and wheat. The model was first calibrated using observed data sets and then validated using independent data sets. Crop management practices (planting date, fertilizer application rate and planting density) were evaluated under projected climate change scenarios for sorghum and wheat production. Likewise, sensitivity of sorghum and wheat crops to a change in climatic variables from the baseline climate also assessed using DSSAT4.6.

The result of observed historical climate analysis showed that stations considered in this study received different amount of annual and seasonal rainfall over the study periods. The annual distribution of rainfall also varied among stations. The result further indicated that the area was generally characterized by high inter annual and spatial rainfall variability. On the other hand, the area under investigation become warmer over the last three decades. The highest increase in temperature was observed during *kiremt* season when compared to that of *belg* season or the annual mean temperature.

The result of projected future climate showed that the sites will experienced warmer temperature by mid and end century than today. And on average, maximum temperature will increase by 1.8 ^{o}C and 2.2 ^{o}C by 2050s and 2080s respectively under the medium emission scenario; and 2.4 ^{o}C and 3.8 ^{o}C for the same period but under the highest emission scenario.

Likewise, minimum temperature will increase on average by 1.8 ^{o}C and 2.4 ^{o}C under the medium emission scenario and 2.7 ^{o}C and 4.7 ^{o}C with highest emission scenario, respectively by the 2050s and 2080s. The rate of warming is expected to be higher towards the end of the century at all stations studied, particularly under the highest emission scenario.

Likewise, warming is expected in future climate during all seasons. The result indicated that mean temperature during Kiremt and Belg seasons will increase in all stations both in the mid and end term period under the prescribed emission scenarios. On the other hand, mean temperature increase during Belg season particularly at Mekelle and Kobo will be higher as compared to mean annual and Kiremt temperature under both emission scenarios.

Regarding the future rainfall, the result indicated that annual rainfall in the region will increase on average by 2.8% to 16.6% and by 8.4%-29% varied with emission scenarios and stations by the 2050s and 2080s, respectively. More specifically, conditioned on emission scenarios considered, annual rainfall at Kobo, Sirinka and Mekelle is expected to increase by 8.5-15.6%, 12.2-16.6% and 2.4-8.4% by 2050s respectively. Likewise, by the 2080s, it is expected to increase by 8.6-17.8%, 10-29% and 8.4-15.3%, for Kobo, Sirinka and Mekelle respectively. Considering the seasonal changes of future rainfall, the result showed that all stations will have an increasing trend of kiremt rainfall totals. However, the magnitude of change in kiremt rainfall will vary spatially. Accordingly, Mekelle will see minimal increase in kiremt rainfall total both in the 2050s and 2080s under the medium emission scenario.

Moreover, results on the impact of future climate on sorghum and wheat production revealed that yield response of both crops vary among climate models used. However, the result showd a general tendency of decreasing yield of sorghum and expected to decrease by 1.2-23% conditioned on emission scenarios, period of analysis, variety and the study location. Likewise, regardless of location, variety and emission scenarios, productivity of sorghum would drastically decrease towards the of end of the century (2080s) than that of the mid-century (2050s).

Similarly, the impact of future climate on production of wheat varied with also on the types of emission scenarios, climate model and period of analysis considered. However, on average, wheat yield is expected to increase from 2.2-6.6% by 2050s while the productivity of the crop might decline by the end of the century under the highest emission scenarios. The result also revealed that sorghum yield is highly sensitive to temperature change and less benefited from elevated atmospheric CO2. However, sensitivity of sorghum for varied climatic and environmental variables conditioned on variety and growing location. Nonetheless, the yield response of melkam will be improved even the rise of temperature greater than 3 ^{o}C combined with an increase of rainfall by 10%. In general, wheat yield is sensitive to increased temperature, rainfall variability and carbon dioxide concentration.

The result further revealed that early planting of sorghum could reduce and/or improve the production under the future climate. In contrast, both early and late planting might not improve wheat and sorghum production in future climate. Moreover, nitrogen fertilizer application might be used to enhance the production of wheat and sorghum. Increase in seed rate/plant population also revealed significant role reducing the negative impact of climate change. Hence, field management practices such as changing planting date, nitrogen fertilization and adjusting planting density could be used as adaptation option to reduce the adverse impact of climate change in the study area.

5.2. Recommendation

Based on the findings of this study, it is recommended that

- Assessment of climate change impacts on crop production as well as ecosystem service should consider application of multiple climate model (GCMs)
- Future policy options need to fine-tune climate change adaptation technologies based on agro-ecological settings
- Agricultural research and development support systems need to focus on developing/adapting crop types and/or varieties resistant to heat and drought stress with appropriate level of extension and promotion services
- Focus need to set on integrated farm level crop management practices to increase the yield of wheat and sorghum under climate change conditions in the study area.
- Modeling approach that integrates the biophysical, economic, social and institutional aspects of a system under study could be helpful to assess the impact of climate change on crop production and explore more appropriate adaptation strategies for further studies.

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