ANALYSIS OF CLIMATE VARIABILITY AND CHANGE AND ITS IMPACTS ON WATER PRODUCTIVITY AND NUTRIENT USE EFFICIENCY OF MAIZE (*Zea mays*) IN THE GREAT ETHIOPIAN RIFT VALLEY BASINS

PHD DISSERTATION

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HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

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ANALYSIS OF CLIMATE VARIABILITY AND CHANGE AND ITS IMPACTS ON WATER PRODUCTIVITY AND NUTRIENT USE EFFICIENCY OF MAIZE (*Zea mays*) IN THE GREAT ETHIOPIAN RIFT VALLY BASINS

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DEDICATION

This dissertation is dedicated to all subsistence farmers in developing countries who are tirelessly fighting the impacts of climate variability and change to feed the ever-growing population.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this dissertation 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 dissertation. Any scholarly matter that is included in the dissertation has been given recognition through citation. This dissertation is submitted in partial fulfillment of the requirements for a PhD degree at Hawassa University. The dissertation is deposited in the Hawassa University Library and is made available to borrowers under the rules of the Library. I solemnly declare that this dissertation has not been submitted to any other institutions anywhere for the award of any academic degree, diploma or certificate.

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LIST OF ACRONYMS AND ABBREVIATIONS

AE	Agronomic Efficiency
AETc	Actual Evapotranspiration of Crop
AfSIS	Africa Soil Information Service
AR3	The Third Assessment Report
AR5	The Fifth Assessment Report
ARBWA	Awash River Basin Water Audit
MoARD	Ministry of Agriculture and Rural Development
CIAT	International Centre for Tropical Agriculture
CMIP3	Coupled Model Inter-comparison Project Phase 3
CMIP5	Coupled Model Inter-comparison Project Phase 5
CORDEX	Coordinated Regional Downscaling Experiment
CRV	Central Rift Valley
CV	Coefficient of Variation
DSSAT-CSM	Decision Support System for Agro-Technology Transfer Cropping System Model
ECRGE	Ethiopian Climate Resilient Green Economy
EIAR	Ethiopian Institute of Agricultural Research
EPA	Environmental Protection Authority
FAO	Food and Agricultural Organization of the United Nations
GCM	Global Climate Model
GDP	Gross Domestic Product
GHGs	Greenhouse Gasses
GRVB	Great Rift Valley Basins
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
Kc	Crop Coefficient
LGP	Length of Growing Period
LULC	Land Use Land Cover
MARC	Melkassa Agricultural Research Center
masl	Meters Above Sea Level
MEF	Ministry of Environment and Forest of Ethiopia

LIST OF ACRONYMS AND ABBREVIATIONS (Cont…)

MoARD	Ministry of Agriculture and Rural Development of Ethiopia
MoWE	Ministry of Water and Energy of Ethiopia
NMA	National Meteorology Agency of Ethiopia
NUE	Nutrient Use Efficiency
PCI	Precipitation Concentration Index
PE	Physiological Efficiency
PET	Reference Crop Evapotranspiration
PETc	Potential Evapotranspiration of Crop
PNB	Partial Nutrient Balance
ppm	Parts Per Million
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDf	Root Depth fraction
RE	Recovery Efficiency
SRES	Special Report on Emission Scenario
SWf	Soil Water fraction
TLS	Total Least Square
UNESCO	The United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
WBISPP	Woody Biomass Investment Strategy Plan and Program
WHC	Water Holding Capacity
WRB	World Reference Base
WRSI	Water Requirement Satisfaction Index

Table of Contents

DEDICATION i
STATEMENT OF THE AUTHOR ii
ACKNOWLEDGMENTS iii
LIST OF ACRONYMS AND ABBREVIATIONS iv
LIST OF TABLES xi
LIST OF FIGURES xii
LIST OF TABLES IN APPENDIX xiii
LIST OF FIGURES IN APPENDIX xiv
LIST OF MANUSCRIPTS xv
ABSTRACT xvi
CHAPTER ONE 1
1 General 2
- 1.1 Introduction 2
- 1.2 General Objective 5
- 1.3 Specific Objectives 5
- 1.4 Research Hypothesis 6
- 1.5 Materials and Methods 7
  - 1.5.1 General description of the Great Rift Valley Basins 7
    - 1.5.1.1 Location and topography 7
    - 1.5.1.2 Climate 8
    - 1.5.1.3 Geology and soil 9
    - 1.5.1.4 Vegetation 10
    - 1.5.1.5 Land use/land cover 11
    - 1.5.1.6 Farming system 12
  - 1.5.2 Description of the experimental sites 12
    - 1.5.2.1 Location 12
    - 1.5.2.2 Climate 13
    - 1.5.2.3 Soil and farming systems 13

1.6 Dissertation Organization 14

1.7 Reference 16

CHAPTER TWO 20

2 Climate Trend, Variability and Change Analysis for Rainfed Farming in The Great Rift Valley Basins of Ethiopia 21

2.1 Introduction 22

2.2 Materials and Methods 24

2.2.1 Study area description 24

2.2.2 Climate analysis for baseline climate 25

2.2.2.1 Baseline climate data sources 25

2.2.2.2 Data quality assessment 25

2.2.3 Climate analysis in the projected periods 26

2.2.3.1 Climate data and models used 26

2.2.3.2 Representative concentration pathways and time frame used 27

2.2.3.3 Climate data downscaling 28

2.2.4 Soil and crop data 28

2.2.5 Data analysis 29

2.2.5.1 Climate trend and variability analysis 29

2.2.5.2 Determination of growing season characteristics 31

2.2.5.3 Dry-spells determination 33

2.2.5.4 Determination of seasonal water requirement satisfaction index 33

2.2.5.5 Climate change analysis 35

2.3 Results and Discussions 37

2.3.1 Rainfall characteristics, trends and variability in the GRVB 37

2.3.1.1 Rainfall characteristics 37

2.3.1.2 Rainfall trends 38

2.3.1.3 Rainfall variability 40

2.3.2 Main growing season characteristics ... 41
2.3.2.1 Onset and cessation ... 42
2.3.2.2 Length of growing period (LGP) ... 44
2.3.2.3 Dry spell occurrence during the main growing season ... 45
2.3.3 Climate changes in the projected climate scenario ... 49
2.3.3.1 Projected changes of precipitation in the GRVB ... 49
2.3.3.2 Projected changes of temperature in the GRVB ... 51
2.3.3.3 Projected changes in growing season characteristics ... 54
2.3.3.4 Dry Spell occurrence under climate change ... 57
2.3.3.5 Water requirement satisfaction index (WRSI) under changed climate ... 58
2.4 Conclusions ... 60
2.5 Reference ... 61
CHAPTER THREE ... 65
3 Climate Induced Yield Level, Variability and Yield Gap of Maize in the Semi-arid Central Rift Valley of Ethiopia ... 66
3.1 Introduction ... 67
3.2 Materials and Methods ... 69
3.2.1 Crop model used and its description ... 69
3.2.2 Crop model input datasets ... 70
3.2.2.1 Soil data ... 70
3.2.2.2 Crop and management data ... 70
3.2.2.3 Weather data ... 71
3.2.3 Data Analysis ... 72
3.2.3.1 Crop model evaluation ... 72
3.2.3.2 Analysis of yield level, variability and gap ... 74
3.3 Results and Discussions ... 78
3.3.1 Soil physico-chemical characteristics of the experimental sites ... 78

3.3.2 Crop model evaluation 80
3.3.3 Current yield level, variability and gap 83
3.3.3.1 Relationships of climate and maize grain yield in the CRV 83
3.3.3.2 Potential and water limited yield level in the CRV 86
3.3.3.3 Yield level and variability under different nutrient conditions 88
3.3.3.4 Yield gap analysis 89
3.4 Conclusions 92
3.5 Reference 93
CHAPTER FOUR 98
4 Assessing Impacts of Climate Variability and Change on Water Productivity and Nutrient Use Efficiency of Maize in the Semi-arid Central Rift Valley of Ethiopia ... 99
4.1 Introduction 100
4.2 Materials and Methods 103
4.2.1 Climate data source and climate models used 103
4.2.2 Climate change scenario and time frame used for the Study 103
4.2.3 Crop simulation model used 103
4.2.4 Crop management scenarios for climate change impact assessment 105
4.2.4.1 Determination of planting dates 105
4.2.4.2 Nutrient management scenario 105
4.2.4.3 Water availability scenarios 106
4.2.5 Determination of water productivity (WP) 106
4.2.6 Determination of nutrient use efficiency 107
4.2.7 Uncertainty assessment for climate impact projections 108
4.3 Results and Discussions 109
4.3.1 Baseline and projected changes in hydro-meteorological variables 109
4.3.1.1 Changes in temperature 109
4.3.1.2 Changes in rainfall in the study sites 110

    - 4.3.1.3 Changes in evapotranspiration 110
  - 4.3.2 Impact of climate change on maize production in the CRV of Ethiopia..... 111
  - 4.3.3 Trends of resources use efficiency of maize in the CRV 115
    - 4.3.3.1 Baseline water productivity of maize under different nutrient levels .. 115
    - 4.3.3.2 Projected water productivity under different nutrient levels 117
    - 4.3.3.3 Impact of climate variability and change on nutrient uptake and NUE 121
- 4.4 Conclusions 132
- 4.5 Reference... 133

CHAPTER FIVE 139

5 General Summary and Conclusions 140

- 5.1 Summary 140
- 5.2 Conclusions 143
- 5.3 Recommendations 144

Appendices.. 145

BIOGRAPHICAL SKETCH 155

LIST OF TABLES

Table		Page
2.1	Detailed information on rainfall and temperature data of stations in the GRVB	25
2.2	Description of climate models used in this study	27
2.3	Soil parameters used for water balance estimation	29
2.4	Annual and seasonal rainfall trend (mm/yr) in the GRVB during 1981-2010	39
2.5	Rainfall variability and PCI of selected stations in the GRVB, 1981-2010	40
2.6	Changes in temperature (°C) in the GRVB relative to 1981-2010	52
2.7	Changes in total number of dry spell length of consecutive 7 days and more for future period with respect to 1981-2010 simulated by HadGEM2-ES_RCA4 model	57
2.8	Maximum dry spell length of main season (by HadGEM2-ES_RCA4 model)	58
2.9	Changes in WRSI for early, medium and late maturing maize	59
3.1	General agronomic information for phenology and grain yield of maize cultivar	71
3.2	Selected properties of Melkassa and Ziway soils used in DSSAT simulations	78
3.3	Simulations vs observed traits statistics for model evaluation	82
3.4	Pearson correlation coefficient (r) of simulated maize grain yield with seasonal climate variables during the baseline period	83
3.5	Seasonal variations in climate variables and potential/water limited maize grain yield during 1981-2010, n = 30 for Melkassa and 1984-2010, n=27 for Ziway)	87
4.1	Representative concentration scenarios, their time coverage and CO2 concentration used in this study	103
4.2	Baseline and future period crop production-influencing factors in the CRV	109
4.3	Changes in grain yield (GY) (Mg/ha) of maize under water limited (WLY) and potential (PY) simulation for mid and far period with respect to the base period	112
4.4	Grain yield (Mg/ha) and water productivity (kg[yield]/ha per mm [ET]) in the baseline and projected periods under different levels of nutrient application	117
4.5	Changes in seasonal N &P uptake in the future periods relative to baseline using ensemble average of four climate models' climate scenario	123
4.6	NUE as affected by levels of NP application in the CRV during 1981-2010	125
4.7	Simulated changes in N-UE under varying N level relative to baseline period	127
4.8	Simulated changes in P-UE under varying P level relative to baseline period	128

LIST OF FIGURES

Figure		Page
1.1	Map of the study location (GRVB)	7
2.1	Agroecological map of the GRVB	24
2.2	Bimodal (Belg and Kiremt) rainfall distribution of stations in the GRVB	31
2.3	Bimodal (long and short season) rainfall distribution in the GRVB	38
2.4	Onset date of the main rain season of stations in the GRVB	42
2.5	Cessation date of the main rain season in the GRVB	43
2.6	Length of growing period (LGP) of selected stations in the GRVB	44
2.7	Onset, cessation and LGP of main growing season, 1981-2010	45
2.8	Probability of dry spell occurrence of 3, 5 8 and 11 days of selected stations in the GRVB	46
2.9	Seasonal WRSI for a) medium & b) early maturing maize at Melkassa and c) medium & d) early maturing maize at Ziway	47
2.10	Seasonal WRSI of medium (a) and late maturing maize (b) at Assela	48
2.11	Projected changes in annual rainfall in the future period relative to 1981-2010	50
2.12	Changes in annual average temperature (ºC) as projected by HadGEM2-ES_RCA4 RCM in near, mid and end of century relative to the baseline	53
2.13	Simulated changes in onset (solid bar) and cessation (patterned bar) during 2011-2040 relative to 1981-2010 period	55
2.14	Changes in length of growing period during 2011-2040 relative to 1981-2010 period.	56
3.1	Observed vs. simulated days to emergence (a & b), days to anthesis (c & d), days to maturity (e & f) and maize grain yield (Mg/ha) (g & h) for Melkassa-2 maize variety	80
3.2	Observed vs model predicted grain yield (a) and aboveground biomass (b) of maize under different levels of P application during 2017 (Melkassa)	81
3.3	Relationship of simulated water-limited yield versus growing season rainfall (a) and evapotranspiration (b)	85
3.4	Yield variabilities and gap under conventional and unlimited nutrient supply	89
3.5	Yield gap of maize in the CRV of Ethiopia during 2007-2015 season	90
3.6	Potential and water limited yield variabilities and gaps in the CRV	92
4.1	Water productivity trends of rainfed maize under optimum (WPopt) and recommended (69-20NP) (WPrec) fertilizer rates at Melkassa, CRV of Ethiopia	116
4.2	Cumulative seasonal N&P uptake of maize at Melkassa (a&b) and Ziway (c&d)	122

LIST OF TABLES IN APPENDIX

Appendix Table		Page
1	Model comparison for annual and seasonal precipitation of the GRVB for impact assessment	145
2	Model comparison for annual and seasonal temperature of the GRVB for impact assessment	145
3	Percentage changes in monthly and annual rainfall as projected by different Global Climate Models (GCMs) downscaled by RCA4 RCM for two emission scenarios for the 2071 - 2100s relative to the baseline period (1981-2010) at Melkassa	146
4	Changes in monthly and annual rainfall as projected by different General Climate Models (GCMs) downscaled by CLMcom RCM for two emission scenarios for the 2071 -2100s relative to the baseline period (1981-2010) at Melkassa	146
5	Modelling approaches of DSSAT CERES-Maize crop model	147
6	Genetic coefficients of maize cultivars calibrated in DSSAT-CSM model	147
7	Experimental information (mean values from 23 Kg ha-1 N and 20 Kg ha-1 P treatment level)	148
8	Projected percent changes in seasonal rainfall (PCP), actual evapotranspiration (ET), mean grain yield (GY) and water productivity (WP) in the mid and far period with respect to baseline period	148
9	Projected changes in seasonal rainfall (PCP), actual evapotranspiration (ET), mean grain yield (GY) and water productivity (WP) in the mid and far period with respect to base period at Ziway	149

LIST OF FIGURES IN APPENDIX

Appendix Figure **Page**

1 Projected changes in rainfall as projected by ensemble average of RCA4 based models during mid-century relative to the base period 149
2 Internal variability of the climate system simulated by individual models for the GRVB 150
3 Seasonal N and P uptake of maize at Melkassa and Ziway during high and low rainfall years simulated by DSSAT crop model 150
4 Cumulative N uptake under good and bad years during baseline and mid period at Melkassa 151
5 Cumulative P uptake under good and bad years during baseline and mid period at Melkassa 152
6 Water productivity simulated by DSSAT cropping system model under different levels of fertilizer rate at Melkassa, CRV of Ethiopia 152
7 Phosphorous calibration trial (a), NP fertilized vs unfertilized plot (b) and nearby farmers field (c) at Ziway in 2011 main season 153
8 Pictures taken from field experiment conducted at Melkassa during 2017 main season 154

LIST OF MANUSCRIPTS

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Analysis of Climate Variability and Change and its Impacts on Water
Productivity and Nutrient Use Efficiency of Maize (*Zea mays*)
in the Great Ethiopian Rift Valley Basins

ABSTRACT

Climate variability and change are a global phenomenon affecting many nations. Smallholder farmers in Ethiopia have been facing severe climate related hazards, in particular highly variable rainfall and severe droughts that negatively affect their livelihoods. Anticipated climate change is expected to aggravate some of the existing challenges and impose new risks beyond the range of current experiences. This study aimed at understanding current climate variability and future climate change, and its associated impacts in particular for maize production. The climate analysis was conducted in the Great Rift Valley Basins (GRVB), which represents diverse agroecology and farming systems. The climate variability and change impact study were conducted in the Central part of the Rift Valley (CRV), which represent a major cereal-based farming system of the semi-arid environments of Ethiopia. Empirical statistical analyses using field experimental data in combination with crop-climate simulation modelling were used to achieve the objectives of the study. A high spatial resolution regional climate models and a well-known crop growth simulation model were used for the modelling analysis, which is an innovative feature of the methodology used in this thesis. The analysis revealed that rainfall exhibited high inter-seasonal variability (coefficient of variation 13-37%) during the period 1981-2010 in the GRVB. The mean annual temperature significantly increased by +0.43 ºC [0.27 ºC to 0.58 ºC] per decade in the same period. Projections for future climate suggested that annual rainfall will change by -25 to +6% and the annual temperature is expected to increase in the range of 2.5-5.1ºC by the end of this century. A corresponding change in length of growing period (LGP) from -5.66 to -25.5% for central semiarid and +3.9 to -16.4% for central sub-humid highlands was simulated in the near century. Maize grain yield was strongly ($P<0.01$) and positively correlated with seasonal rainfall ($r=0.67$-0.69) in the CRV while day temperature affected grain yield negatively ($r= -0.44$) at Ziway ($P<0.05$) during the simulation period. Simulated water-limited yields showed high inter-annual variability (coefficient of variation, ~24%) and about 47% of this variability was explained by the *variation in growing season rainfall. The observed farmers' yield was 28, 48 and 57% lower than the researcher-managed, water--limited and potential yield of the crop, respectively, indicating wide maize yield gap in the region. Analysis of climate change scenarios showed that maize yield will decrease on average by 16.5 and 23% by mid and end of this century, respectively due to climate change. Similarly, water productivity is expected to decline on average by 2.2 and 12% in the CRV by mid and end centuries with respect to the baseline. Nutrient uptake and corresponding nutrient use efficiency (NUE) might also be negatively affected by climate change. Phosphorus uptake probably will decrease in the CRV on average by 14.5 to 18% by mid-century. Nitrogen and P use efficiency indicators showed decreases in the range between 8.5 to 10.5% and between 9.3 to 10.5%, respectively by mid-century relative to the baseline average. The simulation under no water and nutrient limitation condition ensured improvements of both water and nutrient use efficiency in the changed climate which could ensure modest production in the future. The high estimated impact of climate variability and changes on crop yield and associated resources use in the CRV imply greater risks on rainfed crop production in the region. Hence, the study recommends further assessment of potential adaptation options and economic impact of climate related risks in the region to provide full-fledged evidence for better policy decisions.*

Key: Length of growing period, yield gap, Regional climate model, Central Rift Valley, Resources use efficiency, Ethiopia.

CHAPTER ONE

1 General

1.1 Introduction

Climate variability and change are amongst the most important environmental challenges of the 21St century. It has been widely acknowledged that the earth's climate at global, regional and local scales has undergone significant change over periods ranging from decades to millions of years (IPCC, 2007a). Observations over the past century show that surface temperatures have warmed in a statistically significance sense over most of the earth's surface (Trenberth et al., 2007). According to the Intergovernmental Panel on Climate Change (IPCC), there is significant warming occurring globally as well as in the Sub-Saharan African countries (IPCC, 2014) manifested by observed increase in the number of warm spells and a decrease in extremely cold days (Suryabhagavan, 2017). The earlier reports of IPCC also warned that, climate change has already and will further increase climatic variability and the frequency and severity of extreme weather events in the region and elsewhere (IPCC, 2012).

Scientific evidence indicates that anthropogenic factors are the major contributors to the prevailing global climate change (Forster et al., 2007; IPCC, 2013; IPCC, 2014). After thorough assessment of the causes of global temperature change, IPCC concluded that there has been a significant anthropogenic warming over the past 50 years over each continent except the Antarctica (IPCC, 2007b). The atmospheric concentration of greenhouse gases (GHGs) such as carbon dioxide, methane and nitrous oxide has substantially increased over time. For example, the carbon dioxide concentration has increased from 280 ppm (pre-industrial level) to about 391 ppm in 2011; a 40% increase due to human activities (IPCC, 2013). The global average temperature has increased by 0.85 ºC [0.65 to 1.06] over the period 1880 to 2012 (IPCC, 2014) and observed changes in rainfall patterns with an increased frequency of extreme events (IPCC, 2012).

Human-influenced climate change is becoming an observed phenomenon affecting physical and biological systems across the globe (Rosenzweig, 2013). The majority of observed impacts are related to temperature changes and are located in the northern high- and mid-latitudes. However, new evidence is emerging that demonstrates the impacts are related also to precipitation changes and that climate change is impacting systems and sectors beyond the Northern Hemisphere (Rosenzweig, 2013).

These climate related challenges has considerable pressure on the development of the Sub-Saharan Africa countries through its enormous impact on sectors including agriculture, human health, livestock and the economy (Confalonieri et al., 2007; Thornton et al., 2011; Oscar et al., 2015). However, agriculture is among the sectors most sensitive and inherently vulnerable to climate variability (Boko et al., 2007; Müller et al., 2011). The strong dependence of agriculture on climate made agricultural systems inherently vulnerable to climate variability (Challinor et al., 2007; Thornton et al., 2011; Ademe et al., 2019) and climate change is expected to increase this vulnerability (Thornton et al., 2010; Kassie et al., 2015). The impacts of increased temperature from global warming and changes in rainfall patterns resulting from climate change are expected to reduce agricultural production and put further pressure on marginal land (Lobell and Field, 2007).

Various global and regional studies warn that progressive climate change is expected to negatively affect crop productivity in most parts of the world (Wheeler and von Braun, 2013) and particularly in Sub-Saharan Africa (Müller et al., 2011; Waha et al., 2012; Cairns et al., 2013). Ethiopia is among the most vulnerable countries in Sub-Saharan Africa due to its great reliance on climate sensitive sectors, particularly agriculture (Thornton et al., 2006; Conway and Schipper, 2011).With the increasing climate induced risks, rain-fed agriculture is projected to become further constrained (Kassie et al., 2015). For instance, a study by Jones and Thornton (2009) indicated that crop yields in Sub-Saharan Africa may decline by10–20% and some regions would be unsuitable for crop farming by the mid of this century. Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems (IPCC, 2014). Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.

There has been evidence of climate change in Ethiopia over the last 50 years (ECRGE, 2015a) and the change is expected to continue in the future (Arndt et al., 2011; Kassie et al., 2015). At the national level, temperatures have increased by an average of around 1°C since the 1960s and the increase has been felt across all regions. Continued temperature increases of 0.8 to 2.7 °C in mean temperatures have been projected and are likely to continue to do so with climate change (ECRGE, 2015a). Rainfall nationally is subject to high variability between years, seasons and regions. Yearly variation around mean rainfall levels ranging from 25% to 50% and evidence of up to 20% decrease in rainfall was observed in some regions of the country (ECRGE, 2015a). Similarly, increased rainfall variability with more frequent extremes is expected in the future (ECRGE, 2015b). The pattern and amount of the *Belg* and *Kiremt* rains could change, which would have major implications for rural livelihoods and food security, particularly in the Great Ethiopian Rift Valley (Ademe et al., 2020).

The observed increases in temperature and high annual variation in rainfall could significantly alter crop agriculture through affecting the efficiency of soil functions. The climate change impact on the major soil functions can be both directly in affecting rate of organic matter decomposition and indirectly through soil moisture availability thereby affecting nutrient availability (Karmakar et al., 2016). Increases in temperature and declines in rainfall drastically decrease soil moisture availability and reduce nutrient availability and uptake. It has long been appreciated that the climate change affects crop production system through affecting nutrient use efficiency (NUE) and water productivity (WP) of the system (Drechsel et al., 2015).

The interactive effects of soil moisture and nutrient availability are two key edaphic factors that determine crop yield (Ziska and Bunce, 2007) and are the most affected by climatic changes. Current nutrient management recommendations of the country are based on an understanding of crop-specific needs for achieving expected yields and soil-specific nutrient supply characteristics but the story will definitely be different under changed climate. Increases in air temperature and changes in precipitation will significantly impact prevailing root zone temperature and moisture regimes. The nature and extent of the change in these two parameters will be site- and soil specific, reflecting meteorological conditions, soil physical factors and other surface characteristics including leaf area index and ground litter stores (Kang et al., 2000).

Given that maize production is predominantly rain-fed, variability and unpredictability of rainfall and increments in temperature has always been a major concern in Ethiopia (Cooper et al., 2008; Kassie et al., 2014; Getnet et al., 2016). It is also clear that, among the diverse agroclimatic zones of the country, the arid and the semi-arid areas which receive the lowest and most erratic rainfall are severely affected by the changing climate. The CRV is one of those regions which experience frequent natural hazards such as recurrent droughts and chronic water stress and are further affected by climate change and its variability (Kassie et al., 2014; Getnet et al., 2016). Although the cropping system of the CRV where the study was implemented is predominantly maize based (Meshesha et al., 2012), scientific evidences suggest that higher temperatures and changing precipitation levels induced by climate variability and change will have a negative effect in terms of maize yields over the coming decades (Kassie et al., 2015) However, less has been known so far how the changing climate affects maize yields in terms of water productivity and nutrient use efficiency in the study region.

1.2 General Objective

The general objective of the study was to assess the impact of climate variability and change on maize production and associated resources use efficiency in the Great Ethiopian Rift Valley Basins.

1.3 Specific Objectives

The specific objective of this study includes

- To assess climate trend, variability and change, and the implication for rainfed farming in the GRVB
- To estimate climate induced yield level, variability and gap of maize crop in the semi-arid CRV of Ethiopia
- To quantify projected impact of climate change on water productivity and nutrient use efficiency in the semi-arid CRV of Ethiopia

1.4 Research Hypothesis

The study draws the following research hypothesis

1. There exist a high climate variability and change that affects the rainfed farming system in the GRVB.
2. There is climate induced yield variability, yield gap and associated changes in resource use efficiency in the CRV of Ethiopia.
3. There will be climate variability and change induced impacts of water productivity and nutrient use efficiency in the CRV of Ethiopia.

1.5 Materials and Methods

1.5.1 General description of the Great Rift Valley Basins

1.5.1.1 Location and topography

The Great Ethiopian Rift Valley is a NNE–SSW to N–Stranding trough 80 km wide in its central portion and 1,000 km long (Figure 1.1). It separates the highlands from the west to the east. Northward, the valley progressively widens out into the complex Afar triple junction, while at its southern end, a 200–300-km tectonically disturbed area marks the transition to the Kenyan Gregory Rift in the Turkana depression (Abbate et al., 2015).

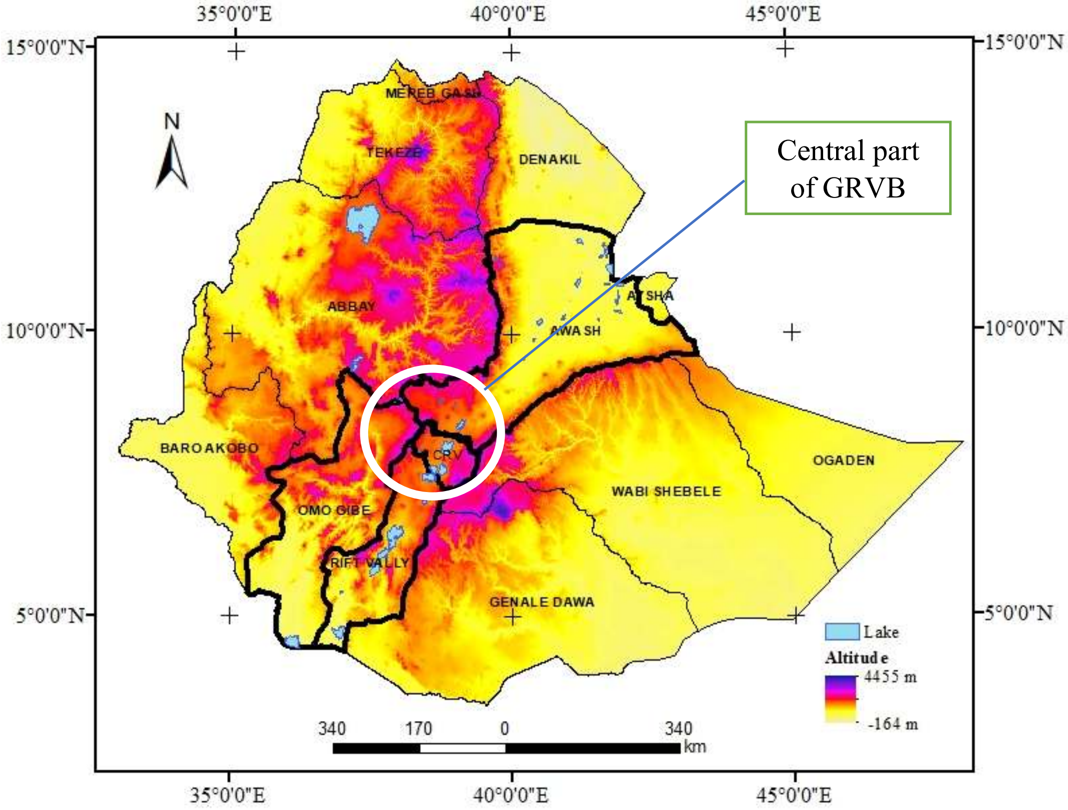

Figure 1.1. Map of the study location (GRVB).

The Ethiopian Rift Valley comprise three river basins (Awash, Omo-Gibe and Rift Valley Lakes basins) and a dry basin (Danakil basin, omitted in this study due to its insignificant agricultural contribution) (MoWE, 2010). The study region (hereafter referred to Great Rift

Valley Basins, GRVB) extends from the northeastern Awash basin to southwestern edges of Rift Valley Lakes and Omo-Gibe basins. The area is situated roughly between 4.5^0 - 12^0 N latitude and 36^0 – 44 ^{0}E longitude with an estimated total area of 243,640 square kilometers (ARBWA, 2013), which is nearly 21.4% of the total land area of the country.

The physiographic features of the GRVB are mainly the results of faulting and volcanism associated with rifting processes (Mechal et al., 2017). From a morphological and geological point of view, the region has been subdivided into three main segments: the northern, central, and southern (Wolde Gabriel et al., 1990; Abbate et al., 2015). The northern rift funnels from the Afar depression, where it is about 100 km wide, to the 80-km long Dubeta Col sill (north of Ziway lake). The central rift, which is 80 km wide, includes most of the lake region and extends southward and has an average elevation of 1,600 m, and the lowest altitude is at Lake Abiyata (1,580 m). The southern Rift Valley narrows up to 60 km, shifts to a N–S trend, and reaches an elevation of 2,000 m, decreasing southward to 1,000 m (Abbate et al., 2015). The typical rift morphology is well developed and the three major physiographic regions, rift floor, escarpment and highland, are clearly visible (Mechal et al., 2017). The major tectonic scarp connects the rift floor with the uplifted plateau; the plateau rises to elevations of 3,200 m a.s.l., whereas the rift floor descends to 1,175 m a.s.l at Lake Abaya (Mechal et al., 2017).

1.5.1.2 Climate

The climate of the GRVB spatially varies as a function of altitude, angle of the sun, distance from oceans, terrain and other factors such as influence of inter-tropical convergence zone (ITCZ) (MoWE, 2010). Altitude greatly influences the climate of the rift system, with the creation of microclimates ranging from cool highlands to hot desert climate (Seleshi and Zanke, 2004). Consequent to the variations in altitude and position of the basins, there exist several agro-ecologies from the arid lowlands to the sub humid and humid highlands (MoARD, 2005).

In general, three seasons exist in the GRVB of Ethiopia (Seleshi and Zanke, 2004). From November to February northeast winds prevail, giving settled dry weather throughout most of the valley (Dry season, locally known as *Bega*). During this period there is little cloud, diurnal temperatures are high and relative humidity is low. Between March and May (short season, locally known as *Belg*) more unsettled weather is experienced due to the convergence of moist southeast winds from the Indian ocean with the northeast airstream. This brings heavy rains south of latitude 6°30' (Lake Abaya), but north of this latitude rainfall is normally light and very unreliable. From June to September (the main rainy season, known as *Kiremt*) come to the northern Rift Valley with the wet winds from the Indian and Atlantic oceans converging over the highlands. Intense rainfalls associated with convective thunderstorms are frequently experienced at the beginning of this period. In the southern part of the valley, however, there is little rainfall between June and August and a secondary peak in September and October. There are thus two rainfall regions within the valley (Smith, 1984).

Rainfall increases with altitude along the Rift Valley escarpment to an approximate annual average of 1600 mm at the 3000 m contour. However above about 1800 m the correlation of rainfall with altitude is particularly poor due to orographic effects (Smith, 1984). In general, the GRVB receive an annual total rainfall from about 160 mm at some locations of lower Awash to more than 1900 mm in the north central highlands of Omo-Gibe basin. Similarly, the mean annual temperature also varies from 10 °C at higher altitude parts of the rift valley lakes to higher than 29 ° C in the lowlands of the study basins (MoWE, 2010).

1.5.1.3 Geology and soil

Since the end of the Tertiary period, the Ethiopian Rift Valley has been the scene of intense volcanic activity and further minor faulting (Smith, 1984; Wolde Gabriel et al., 1990). Consequently, the geological formations are almost entirely volcanic in origin and include both alkaline (basalts) and acidic (rhyolites, ignimbrites, pumices and ash) rock types (Smith, 1984). In general, the rocks covering the area fall into three major groups: pre-rift volcanic rocks, rift volcanic rocks and post rift sediments (Wolde Gabriel et al., 1990; Mechal et al., 2017). The pre-rift rocks (Oligocene–middle Miocene) occur mainly in the escarpment and highland and to a lesser extent in the rift floor. This group mainly comprises basalt and ignimbrite and represents the oldest rocks in the area (Corti, 2009; Mechal et al., 2017). Rift volcanic rocks (upper Miocene–Pleistocene) are mainly exposed in the rift floor and dominated by silicic volcanic rocks. A thick succession of stratoid silicic comprising predominantly ignimbrites with subordinate unwelded tuffs, ash flows, rhyolites and trachyte, which is commonly known as the Nazret group, form parts of the rift floor and also outcrops in the escarpment and highlands (Corti, 2009; Abbate et al., 2015). In the rift floor, the Nazret group is overlain by younger volcanic rocks called the Dino formation which comprises coarse unwelded pumiceous pyroclastic and a complex mixture of different pyroclastic materials such as ash, tuff and ignimbrite. (Abbate et al., 2015; Mechal et al., 2017). Post-rift sediments (Holocene) such as alluvial and lacustrine sediments mainly occur along the lower reaches of the Gidabo River and as patchy deposit along the axial zone of the rift, respectively (Mechal et al., 2017).

Consequent to variations in geological formations, physiography and climate, the soils of the Rift Valley of Ethiopia are quite diverse. Seventeen out of 106 FAO suborders are important in the region, a reasonable proportion for a small area in African terms (Smith, 1984). The most important groupings in terms of total area covered are thus: Vertisols (19.2%), Cambisols (17.9%), Fluvisols (16.2%), Regosols (15.8%), Lithosols (9.5%), Andosols (7.1%) and Acrisols (6.1%). All remaining soil units taken together account for less than 10% of the total area (FAO/UNESCO, 1977; Smith, 1984). These soils are for the most part derived from young rocks of volcanic origin where such soils exhibit good nutrient status since leaching has not proceeded to a very marked degree. However, these young volcanic rocks are generally in many cases are deficient in some plant nutrients, notably phosphate that would challenge agriculture without application of P fertilizers (Smith, 1984; Argaw et al., 1999).

1.5.1.4 Vegetation

As a consequence of the tectonic activity, typical rift morphology (uplifted highlands and downthrown flat plain rift floor) is well developed causing strong contrast in topography and climate within short distances (Mechal et al., 2017). These variations in topography and climate resulted in tremendous variations in the type of vegetation existed across the study area. Makin et al. (1975) for example, classified the southern rift region in to four ecoclimatic vegetation zone. The humid to dry-humid lands are mostly under coffee or other intensive agricultural use. However, these lands were formerly under forest or montane grassland. In the dry sub-humid or semi-arid lands, the vegetation types are characterized by evergreen shrubs, Combretum or allied vegetation. This zone is the most extensive part of the valley floor where it is currently subject to increasing settlement pressure (Argaw et al., 1999). Semi-arid lands with relatively low or erratic rainfall, characterized by dryland acacias with some broad-leaved trees and shrubs.

In general, the vegetation in the Rift Valley is mainly characterized by *Acacia combretum* open woodland, now extensively overgrazed (Woldu and Tadesse, 1990), whereas deciduous woodlands (*Olea europaea*, *Celtis*, *Dodonaea viscosa* and *Euclea*) occupy the escarpments. The montane forest exists between 2000 and 3000 m on the eastern Ethiopian plateaus bordering the rift and is dominated by *Podocarpus gracilior* (Legesse et al., 2004). In the past several decades, tropical meadow-type grassland vegetation and shrublands were also the dominant types of vegetation in the central highlands of the study area. Now, such types of vegetations have been gradually replaced by croplands/settlements and eucalyptus plantations (Desalegn et al., 2014).

1.5.1.5 Land use/land cover

The land use/land cover of the northern portions of the GRVB is dominated by exposed rock with about 34.9% of the total land area followed by cultivated land of about 27% and open shrub land (20.9%) (ARBWA, 2013). Similarly, forest and grass land also comprise about 7.4% and 6.6% respectively of the total land area of Awash Basin (ARBWA, 2013). The southern and central parts of the GRVB is under extensive cultivation with increased land pressure arisen from the expansion of cultivated areas in to increasingly marginal lands at the expense of wood lands (Ariti et al., 2015). The flatter poorer drained bottom lands of the northern catchments of the Omo-Gibe basin are usually not cultivated but are used for dry season grazing and eucalyptus tree plantations (MoWE, 2010). The southern reaches of the GRVB is more sparsely populated with a greater population of natural vegetation. Except in Middle Awash where shrub and pasture lands are being cleared for irrigation, rainfed cultivation is being converted to irrigation in other parts of the basin wherever land and water resources are available (ARBWA, 2013).

1.5.1.6 Farming system

Ethiopia is dominated by small scale crop-livestock mixed farming systems and cereals are the most important food crops occupying about 77% of the total cultivated area. Production technologies are predominantly characterized by low agricultural inputs (fertilizer, improved seeds, pesticides) using traditional farming techniques (Arndt et al., 2011). Similarly, mixed crop-livestock system is the most important farming system in the plateau and the highland areas of the northern and central GRVB which is dominated by smallholder rainfed agriculture with limited but complementary livestock production (ARBWA, 2013). Cattle are mainly kept for draught power, meat and milk while equines are used as pack animals. Sheep, goats and poultry also play a significant role in augmenting household income. Land holdings are generally small with average landholding less than 1.0 ha and are fragmented into a number of plots with different land uses. Cereals and pulses are the main crops in the cropping pattern with some vegetables mainly for market (ARBWA, 2013).

In the past two decades, smallholder vegetable production for local market, export-oriented vegetable, fruit and flower production under irrigation were the major agricultural transformations in the central portion of the Rift Valley (Abera, 2019). Different crops are grown in the region using both the *Belg* and *Kiremt* rains (Legesse et al., 2004). In the rift floor, the main cultivated crop is maize, the staple food in many parts of the region, with teff, wheat, haricot beans and barley, and the plateau land is one of the principal producers of cereals in the country (Legesse et al., 2004).

1.5.2 Description of the experimental sites

1.5.2.1 Location

Assessment of climate variability and change impact on maize production and associated resources use efficiency was conducted in the semi-arid central portion of the Great Rift Valley of Ethiopia, hereafter referred to as the Central Rift Valley (CRV). The sites are situated within the Rift Valley Lakes Basin (RVLB) and partly in the Awash Basin, which are parts of the twelve major Basin systems in Ethiopia. The CRV study region (center-point) is located at about 120 kilometers south of Addis Ababa and it is characterized by an alternating topography with a central valley floor at 1500-1700 meters above sea level (m.a.s.l) and bounded by a western and eastern escarpments with the highest altitudes of over 3000 m.a.s.l (Jansen et al., 2007; Kassie et al., 2015; Abera et al., 2018)

1.5.2.2 Climate

The long term monthly total rainfall and monthly maximum and minimum temperature of the study sites are depicted in Figure 1.2. Climate in the CRV varies markedly with altitude. The annual average daily temperature is about 16 °C in the eastern and western highlands (3000 m.a.s.l) and increases to 21 °C in the central lowlands (~1600 m.a.s.l). Rainfall shows an opposite spatial trend and varies from 600 mm in the central lowlands to about 1600 mm yr^{-1} in the highlands. Based on annual rainfall distribution, the is characterized by a bi-modal rainfall pattern, which is a typical characteristic for the central, eastern and north-eastern parts of Ethiopia (Kassie et al., 2014; Ademe et al., 2019). About 70% of the rainfall is received in the main rainy season from June to September, while the short rainy season stretches from March to May (Getnet et al., 2014; Ademe et al., 2019).

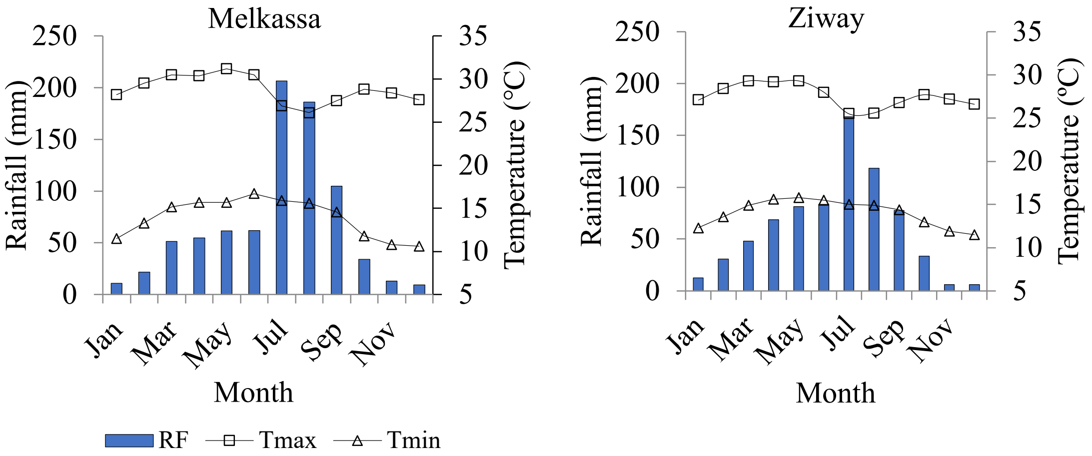

Figure 1.2. Long-term monthly rainfall and temperature of the study sites (1981-2017 for Melkassa and 1984-2017 for Ziway).

1.5.2.3 Soil and farming systems

According to Getnet et al. (2016), eight major soil types are found in the CRV: Luvisols (42%) are the most dominant soil type where the majority of the field experiments were undertaken, while Nitisols (12%) covers most parts of the highland soils of the CRV, Andosols (10%), Cambisols (10%) and Vertisols (8%) also cover large areas in the CRV. The main part of the CRV, which potentially allows both rainfed and irrigated agriculture, covers around 54% of the area and is located on relatively flat land with slopes of less than 8% while about 20% of the CRV is characterized by slopes of 8–16%, potentially suitable for rainfed agriculture and pressurized irrigation. Approximately 18% of the CRV is on slopes of more than 16%, which are not suitable for sustainable arable farming without huge investments in conservation structures, and the remaining 8% is covered by lakes (Getnet et al., 2016).

The predominant livelihood strategy for the majority of the population (about 2 million) in the CRV is small mixed rainfed farming system comprising cereals (maize, wheat, barley and teff) and livestock (Meshesha et al., 2012; Getnet et al., 2014). Maize (*Zea mays*) is the major cultivated crop (26%) and has a significant role in the livelihoods of smallholders in the CRV (Biazin and Stroosnijder, 2012; Getnet et al., 2016) but its production is severely constrained by low soil fertility and water stress during critical growth stages (Senay and Verdin, 2003; Kassie et al., 2014).

1.6 Dissertation Organization

The objectives defined in Section 1.3 are addressed in three complementary research chapters (Chapters 2 to 4), which are followed by general discussion and conclusions (Chapter 5). Chapter 2 aimed at understanding and characterizing agroclimatic variability as well as changes and associated risks with respect to implications for rainfed crop production in the Great Rift Valley Basins of Ethiopia (GRVB). Temporal variability and characteristics of selected rainfall and temperature indices for stations were analyzed and trends were evaluated. It also dealt with projected future changes in rainfall and temperature for three future periods, namely near (2011-2040), mid (2041-2070) and end (2071-2100) centuries relative to the 1981-2010 baseline period and its associated changes in selected agroclimatic indices pertinent to rainfed farming. Projected climate scenarios were developed from a combination of eight GCM-RCMs [GCMs used include CNRM-CM5, EC-EARTH, HadGEM2-ES and MPI-ESM-LR outputs dynamically downscaled by two regional climate models (RCMs)- RCA4 and ClmCOM] and two representative concentration pathways

(RCP4.5 and RCP8.5). The chapter provides an overview of current and future climate trends and indications of climate induced risks on rainfed crop production.

Chapter 3 presents climate induced yield level, variability and yield gaps of maize for the semi-arid Central Rift Valley of Ethiopia during the base period (1981-2010). The widely used Decision Support System for Agro-Technology Transfer Cropping System Model (DSSAT-CSMv4.7) model were used to undertake the simulation analysis. A simulation experiment was carried out with a medium maturing cultivar of maize (Merlkassa-2) using historical weather data of two locations in the semiarid areas of the CRV. The analysis provided quantified information on climate induced yield level, variability and existing yield gaps in the study sites.

Chapter 4 presents observed and projected impacts of climate on maize production and productivity and corresponding effects on the efficiency of water and nutrient uses in the semi-arid Central Rift Valley of Ethiopia. Impact studies were undertaken using DSSAT-CSM crop model and climate scenarios developed from four high resolution GCM-RCM combinations (CNRM-CM5_RCA4, EC-EARTH_RCA4, HadGEM2-ES_RCA4 and MPI-ESM-LR_RCA4) outputs under RCP4.5 and RCP8.5. The chapter quantified the effects of observed and changed climate on maize production, water productivity, and nutrient use efficiency under rainfed and irrigated conditions.

Chapter 5 summarizes and interprets key findings from all the chapters. It also provides conclusive remarks and implications of the main topics of the thesis such as climate variability and change with its associated impacts on water productivity and nutrient use efficiency of maize. Finally, scientific insights and result-based recommendations for climate risk management and pertinent issues for further research are described.

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CHAPTER TWO

Climate Trend, Variability and Change Analysis and Implications for Rainfed Farming in the Great Rift Valley Basins of Ethiopia

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2 Climate Trend, Variability and Change Analysis for Rainfed Farming in The Great Rift Valley Basins of Ethiopia

Abstract

The generally high temporal and spatial climate variability and change in most parts of Ethiopia, where rainfed farming is the main form of crop production, has been the main cause of food insecurity in significant areas of the country. The study aimed at investigating the trend, variability and changes of selected major agroclimatic variables over the Great Rift Valley Basins of Ethiopia (GRVB) during the baseline (1981-2010) and projected (2011-2100) periods. First order Markov chain model for missing rainfall data filling and Mann-Kendall for trend test were used in the analysis of climate data. The result indicated that the main season showed high (50% of station) to very high (25% of stations) variability. Significant ($P < 0.05$) annual and seasonal rainfall trend were observed in some stations in the baseline period. The stations showed varying onset, cessation and length of growing period (LGP). Seasonal water requirement to satisfy maize crop varied annually, date of planting and maturity date. The majority of the season in the semiarid parts of the basin did not meet the total water requirement of medium and late maturing maize. For the projected periods, Majority of the climate models projected a decline in annual rainfall and increase in temperature. HadGEM2-ES_RCA4 model simulation suggested precipitation change varying from +4.2 to -16% and +3.8 to -18% for near period under RCP4.5 and RCP8.5 emission scenarios, respectively. Mean temperature is projected to rise from +0.7 to +1.25 ºC under RCP4.5 to +0.9 to +1.6 ºC under RCP8.5 across the GRVB in the near future and further warming was projected in the mid and far periods. A corresponding change in LGP from -5.66 to -25.5% and +3.9 to -16.4% was also simulated for central semiarid areas and sub-humid highlands, respectively. Similarly, projected increases in-season dry spell length and frequency coupled with seasonal water deficit during the main growing season for semi-arid and sub-humid agroecology further escalate and potentially harm the predominant rainfed based farming of the area. Options to improve water availability during the main season will thus be vital to reduce vulnerability of rainfed crop production in the GRVB.

Key: Agroecology, length of growing period, water requirement satisfaction index

2.1 Introduction

Rainfed farming is the main form of crop production in Ethiopia; like it is for many of the neighboring regions in Africa. However, it is highly variable in most parts of the country both in terms of length of the rainy season and amount of rainfall (Mesay, 2006). In a country, Ethiopia, where irrigated agriculture covers less than 5% of the total cultivated land, natural rainfall is the main source of water for crop production (Awulachew et al., 2010). Hence, rain-fed crop production is the basis of all subsistence farming in most parts of the country, accounting for more than 95% of the land area cultivated annually (Gebremichael et al., 2014).

Rainfall in much of the country is erratic and unreliable, causing variability and associated droughts that have historically been major causes of food shortages and famines (Gebremichael et al., 2014). There exists a significant relation between climate and agricultural production in terms of the timing, variability, and quantity of seasonal and annual rainfall in Ethiopia. According to von Braun (1991), a 10% decrease in seasonal rainfall from the long-term average generally translates into a 4.4% decrease in the country's food production. Hagos et al. (2009) also examined the impact of rainfall variability on the Ethiopian economy, and found that rainfall variability in the country led to a production deficit (20%) and increased the poverty rates (25%) which cost the economy over one third of its growth potential. Similarly, climate variability coupled with climate change could reduce Ethiopia's GDP growth by between 0.5 and 2.5% each year. As a worst case scenario, in 25 years, Ethiopia could have only half the potential total GDP it could have attained (ECRGE, 2015b).

In Ethiopia, the main season (*Kiremt*) contributes the majority of the countries crop production due to significant rainfall reception during this period of the year. Krauer (1988) indicated that *Kiremt* contributes for 50 to 90% of the annual rainfall over major rainfall area of the country and is responsible for 85 to 95% of the production of food crops of the country. Verdin et al. (2005) also explained that, short cycle crops (e.g. wheat, teff, barley) that are cultivated during the *Belg* and *Kiremt* seasons constitute 5 – 10% and 40 – 45% of national crop production, respectively while long cycle crops, such as maize and sorghum, grown during the entire *Belg* and *Kiremt* seasons, constitute for 50% of the national production.

Crop production in the great Rift Valley region is predominantly rain-fed and hence is prone to risks of climate variability and change. Although the region is one of the environmentally vulnerable in the country, reports show that significant rain-fed crop production has been expanded over recent decades (Jansen *et al.* 2007). Exploring options in the basins would thus be an important step to understand the nature, trend and variabilities of the climate to fully utilize its crop production potentials and respond to climatic risks. Very few such studies have been carried out in these areas, of which the majority did not take into account spatial variations across different representative agroecology. Moreover, previous studies mainly focused on area-averaged rainfall constructed from stations having different record periods. Use of these area-averaged rainfall time series constructed from varying number of stations involved in the analysis both in time and over diverse topography may mask the true variability of rainfall (Seleshi & Zanke 2004).

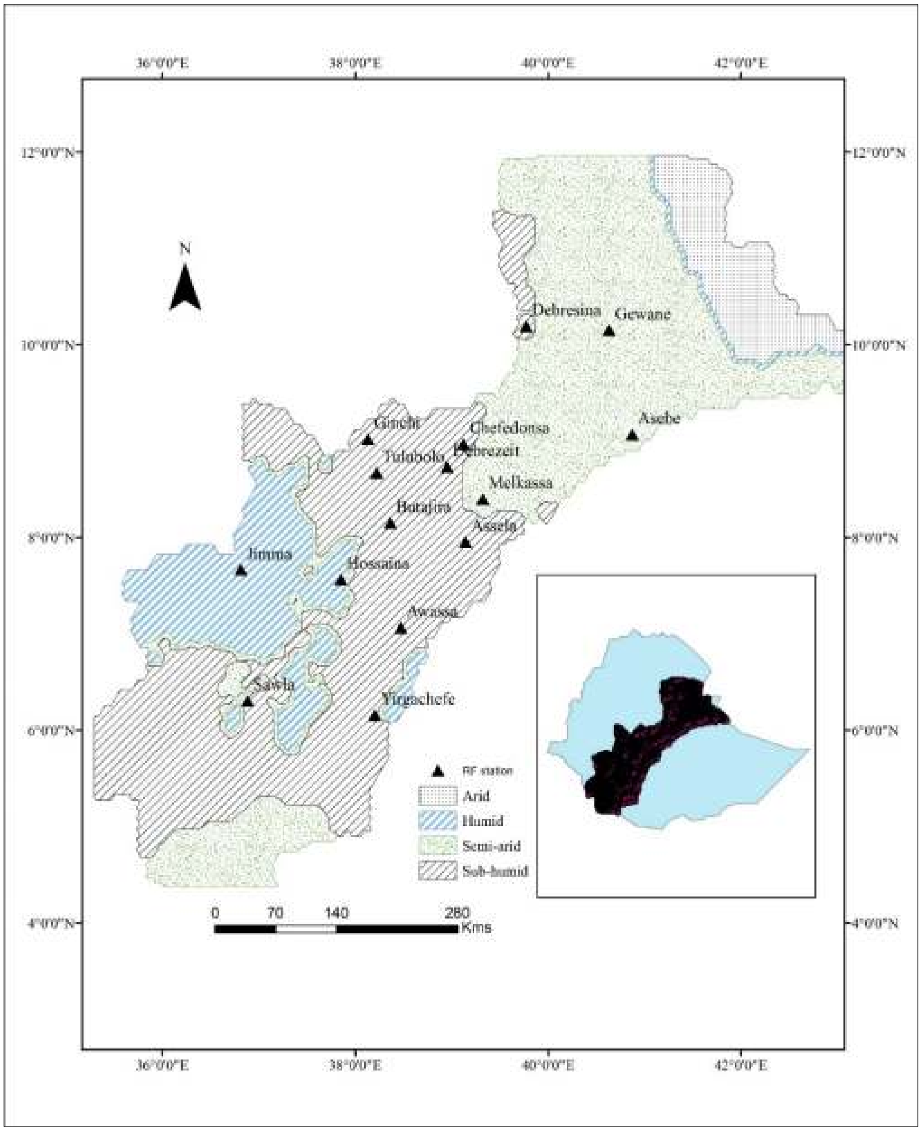
The biophysical characteristics within Ethiopia are highly varied. The terrain spans from the hot arid desert of the Danakil lowland to the mountainous ranges of the Simien. Overlaid on this terrain, agriculture and land-use activities are extremely diverse. This reflects the variation in climate, soil type and cultural practices across the country. This variation complicates policy planning, particularly since responses to build resilience must be grounded in local contexts (ECRGE, 2015a). Clearly understanding the variability of key main season characteristics with respect to differences in agroecology is crucial for the study basins agricultural planning (Segele & Lamb 2005). These would help to optimize the use of available rainfall with respect to meeting crop water requirements.

The study gave adequate attention to rain-fed agriculture as a key element in food security in Ethiopia (NMA 1996a). Given the relative contribution of *Kiremt* to the national crop production and its relative stability in rainfall variability as compared to the *Belg* season (NMA, 1996), understanding the characteristics and variability of *Kiremt* season will be very crucial and sensible. Hence, this study presents the nature, characteristics and variability of the most crucial agroclimatic variables and their corresponding changes in time, with due emphasis on agroecological variations over the great Rift Valley regions of Ethiopia during the main growing season.

2.2 Materials and Methods

2.2.1 Study area description

The study was conducted at selected stations in the GRVB. The selected stations along with their agroecology is depicted in Figure 2.1. The general description of the study area is indicated under chapter one, section 1.5.1.



(Source: IFPRI (HarvestChoice, 2015)

Figure 2.1. Agroecological map of the GRVB.

2.2.2 Climate analysis for baseline climate

2.2.2.1 Baseline climate data sources

Daily measured weather data of 26 representative stations for the present climate, hereafter referred to as baseline, was obtained from the National Meteorological Agency of Ethiopia (NMA) (http://www.ethiomet.gov.et). Among 26 representative stations only Sixteen stations for rainfall and five stations for temperature (Table 2.1) which have long years of a relative complete and quality record for at least 20 and more years were used for analysis. The selection ensured balanced representation of the major agroecology with data records of no more than 10% missing value (Seleshi and Zanke, 2004) during the reference period 1981–2010.

Table 2.1. Detailed information on rainfall and temperature data of stations in the GRVB

Station	Latitude	Longitude	Elevation (m.a.s.l)	Rainfall data Missing (%)	Temp. data Missing (%)	Remark *
Asebe	9.07	40.87	1792	9.54		26
Assela	7.95	39.14	2413	8.5	8.1	30
Hawassa	7.06	38.47	1694	0.03		30
Butajira	8.15	38.36	2000	6.7		28
Chefedonsa	8.97	39.12	2392	5.9		27
Debresina	9.87	39.75	2800	4.7		30
Debrezeit	8.73	38.95	1900	3.4		30
Gewane	10.15	40.63	568	9.9	10.0	22
Ginchi	9.02	38.13	2132	3.9		30
Hossaina	7.56	37.85	2307	4.1		30
Jimma	7.66	36.81	1718	2.0	1.5	30
Melkassa	8.40	39.32	1540	0.03	9.6	30
Sawla	6.30	36.88	1347	8.1		20
Tulubolo	8.67	38.22	2190	4.8		23
Yirgachefe	6.15	38.20	1856	0.9	0.9	30
Ziway	7.93	38.70	1640	2.8		30

* No of years of rainfall data used for analysis

2.2.2.2 Data quality assessment

Before using the data for further analysis, data quality was thoroughly assessed for each station and year. All the climatic data was subjected to rigorous quality check with standard quality control tests including minimum values, maximum values, mean, number of counts, missing values, and maximum differences within a data. Outliers were detected following the Tukey fence approach (Tukey, 1977). The method follows that the inner fences will be located at a distance 1.5 times the interquartile range below the lower and above the upper quartiles and corresponding outer fences are located at the distance 3 times the interquartile range below the lower and above the upper quartiles. Values outside the Tukey fences are considered outliers (Kassie et al., 2015).

Unexpected values of rainfall (negative daily rainfall) and temperature were removed from the data series and set to missing values. To prepare the series for further analyses, the missing values were generated following the first order Markov chain model using INSTAT plus (v3. 37) Software (Stern et al., 2006). Then, the generated data was verified for their physical representativeness of the respective stations in the study sites. Besides, homogeneity of the climate data trend was checked following Von Neumann, Pettitt (Pettitt, 1979), SNHT and Buishand's (Buishand, 1982) homogeneity test criteria (Santos and Fragoso, 2013; Noureldin et al., 2014; Javari, 2016). Consequently, stations which are homogeneous for at least two of the tests were considered for analysis.

2.2.3 Climate analysis in the projected periods

2.2.3.1 Climate data and models used

Projected changes in rainfall and temperature for the study were analyzed based on 8 combinations of 4 Global Climate Model (GCMs) (CNRM-CM5, EC-EARTH, HadGEM2-ES and MPI-ESM-LR) and 2 Regional Climate Models (RCMs) (RCA4 and CLMcom). High resolution dynamically downscaled projected climate data gridded over 0.5° X 0.5° of corresponding stations were used for the period 1981-2100 in combination with RCPs (Moss et al. 2010). The data were obtained from Coordinated Regional Downscaling Experiment (CORDEX) for Africa dataset (http://www.cordex.org). the description of the models used in the study is shown in Table 2.2.

Table 2.2. Description of climate models used in this study

Model	Short Name	Institution	Reference
		GCM Models	
CNRM CERFACS CNRM-CM5	CNRM-CM5	Centre National de Recherches Météorologiques, France	(Voldoire et al., 2013)
EC-EARTH v2	EC-EARTH	EC-Earth Consortium, Europe	(Hazeleger, 2012)
MOHC HadGEM2-ES	HadGEM2-ES	Hadley Met Office Hadley Centre, UK	(Collins, W., 2011)
MPI MPI-ESM-LR	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	(Giorgetta et al., 2013)
		RCM models	
CCLM4.8 CCLM4.8	CLMcom	Climate Limited-Area Modelling Community (www.clm-community.eu)	(Rockel et al., 2008)
SMHI RCA4	RCA4	Sveriges Meteorologiska och Hydrologiska Institut, Sweden	(Samuelsson et al., 2015)

2.2.3.2 Representative concentration pathways and time frame used

The sensitivity of the climate system to an increase in greenhouse gas concentration was considered with low and high emission scenarios. For the past decades, most climate change studies used the Special Report on Emission Scenarios (SRES) of the Coupled Model Inter-comparison Project Phase 3 (CMIP3). Recently, CMIP5 coordinated by the World Climate Research Program in support of the IPCC Fifth Assessment Report (AR5) generated new pathway based on concentration of GHGs in an attempt to improving climate model projections narrowing the uncertainties in projected future climates (Moss et al., 2010; Knutti and Sedláček, 2012, Kassie et al., 2015).

The study considered two Representative Concentration Pathways (RCPs) (RCP4.5 and RCP8.5) among the four RCPs. The RCP4.5, which refers to a radiative forcing pathway of 4.5 W/m^2, in the year 2100, represents a low emission scenario (business as usual scenario), while RCP8.5, which refers to a rising radiative forcing pathway leading to 8.5 W/m^2 in the year 2100 represents a high emission scenario (worst case scenario) (van Vuuren et al., 2011). The time horizon for the climate change scenario analysis was for near-century (2011-2040), mid-century (2041-2070), and for the far century (2071-2100) hereafter referred to as near, mid and far periods, respectively.

2.2.3.3 Climate data downscaling

Climate scenarios were generated by changing the baseline climate data based on outputs from GCM-RCMs/RCPs using the "Delta method" (Wilby et al., 2004). With the delta method, changes in rainfall were created by multiplying the rainfall scenario change factors with the baseline daily values (Eq 2.1), while changes in minimum and maximum daily temperature are obtained by adding the temperature change factors to the baseline daily values (Eq 2.2) (Seaby et al., 2013). Consequently, a projected change in daily rainfall and mean daily temperature from the eight GCM-RCM pairings and two RCPs (RCP4.5 and RCP8.5) by near (2011-2040), mid (2041-2070) and end (2071-2100) century was generated for analysis for each station considered in the study.

$$P_{\Delta}(i,j) = \Delta_p(j) * P_{obs}(i,j) \quad ; \quad \Delta_p(j) = \frac{\overline{P}_{fut}}{\overline{P}_{Ref}} \tag{2.1}$$

$$T_{\Delta}(i,j) = \Delta_T(j) + T_{obs}(i,j) \quad ; \quad \Delta_T(j) = \overline{T}_{fut} - \overline{T}_{Ref} \tag{2.2}$$

where P_{Δ}, and T_{Δ} are delta change perturbed daily climate change variables, P_{obs} and T_{obs} are observed climate variables in the reference period, Δ_P and Δ_T are the changes in climate as simulated by the RCMs, $\bar{P}$ and $\bar{T}$ are daily climate means by annual basis, the index 'ref' and 'fut' indicates the reference and future period, respectively.

2.2.4 Soil and crop data

Soil parameters required for analysis (Water holding capacity and soil depth) were obtained from Africa Soil Information Service (AfSIS) (http://www.africasoil.net) soil database gridded over 0.25° X 0.25° for the study locations (Table 2.3). The parameters obtained were checked for its representativeness for some of the stations with available measured data. Crop data such as maize crop coefficient (Kc), root depth fraction of maize (RDf) and soil water fraction (SWf) required for estimating seasonal water requirement satisfaction index (Stern et al., 1982; Senay and Verdin, 2003) were obtained from FAO database (FAO, 1998).

Table 2.3. Soil parameters used for water balance estimation

Station	Soil depth (cm)	WHC (mm/m)	Station	Soil depth (cm)	WHC (mm/m)
Assebe	200	249	Hawassa	200	326
Assela	100	249	Hossaina	200	305
Butajira	200	301	Jimma	100	282
Chefedonsa	100	214	Jinka	200	282
Debresina	200	300	Melkassa	200	370
Debrezeit	100	278	Tulubolo	100	223
Gewane	200	252	Yirgachefe	200	246
Ginchi	200	205	Ziway	150	170

2.2.5 Data analysis

2.2.5.1 Climate trend and variability analysis

Climate trend analysis

The Mann-Kendall test was employed to look at the existence of statistically significant trend in the observed agro-meteorological variables (Partal and Kahya, 2006) and the magnitude of the trend was assessed using the Sen's method (Salmi et al., 2002). Given a dataset consisting of X values with sample size n, the Mann-Kendall calculation begins by estimating the S statistic given by:

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}\left(X_j-X_i\right)\text{............for } j>i \qquad (2.3)$$

Statistical studies indicated in various literatures such as Mann (1945) and Kendall and Stuart (1967), for any sample with $n \geq 8$, the distribution of S approaches the Gaussian form with mean equating to zero and the variance V(S) given by:

$$V(S)=\frac{n(n-1)(2n+5)-\sum_{m=1}^{n} ti(m-1)(2m+5)m}{18} \qquad (2.4)$$

where: ti is the number of ties of length m. The statistic S is then standardized (Z value) and its significance was estimated from the normal cumulative distribution function as follows:

$$Z=\begin{cases} \frac{S-1}{\sqrt{V(S)}}, & S>0 \\ 0, & S=0 \\ \frac{S+1}{\sqrt{V(S)}} & S<0 \end{cases} \qquad (2.5)$$

The decision to either reject or accept the null hypothesis was then made by comparing calculated Z with the critical value at a chosen level of significance. Sen's Slope Estimator is also a commonly used non-parametric test by which true slope (change per year) of a trend is estimated (Salmi et al., 2002). Sen's test is used when the trend is assumed to be linear.

$$f(t) = Qt + B \qquad (2.6)$$

where f(t), is increasing or decreasing function of time, i.e. the trend Q, is the slope and B, is the intercept (constant). The slope of each data pair Qi was calculated as:

$$Qi=\frac{Xj - Xk}{j - k} \qquad (2.7)$$

where j> k and, if there is n number of Xj in the time series, we get as many as $N=\frac{n\,(n-1)}{2}$ slope estimates of Qi. Then the values of Qi are ranked from small to large; the median of which is the Sen's slope (Q):

$$Q=\begin{cases} Q_{\left[\frac{N+1}{2}\right]}, & \text{\&if N is odd} \\ \left(Q_{\left[\frac{N}{2}\right]}+Q_{\left[\frac{N+1}{2}\right]}\right), & \text{\&if N is even} \end{cases} \qquad (2.8)$$

The initial value of the Z test statistics S is assumed to be zero, implying no trend. If a data value from a later time period is found to be greater than the data value from an earlier time period, then S is incremented by one. On the other hand, if the data value from the later time period is lower than that of the earlier period, the Z test statistics S is reduced by one. The overall result of all increments and decrements provides the final S value which lies between -1 and +1. The null hypothesis of the Z test is that no change has occurred during the time (no trend). Whereas the alternative hypothesis of the Z test is that a significant change has occurred over the time.

Climate variability analysis

Precipitation Concentration Index (PCI) and Coefficient of Variation (CV) were used as descriptors of rainfall variability. These descriptors have been widely used in many rainfall variability studies in Ethiopia and elsewhere (example: Bewket and Conway, 2007; Kassie et al., 2015; Bekele et al., 2016). Precipitation Concentration Index (PCI) was calculated using the following equation after Milan et.al, 2016 and Bekele et al. (2016)

$$\mathrm{PCI} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \qquad (2.9)$$

where Pi is the rainfall amount of the ith month. Precipitation concentration index values below 10 indicate uniform rainfall distribution; values between 11 and 15 indicate moderate rainfall distribution; values between 16-20 indicate irregular distribution and values of above 20 indicate very strong irregularity of rainfall distribution (Milan et.al, 2016). The coefficient of variation (CV) was calculated using the following relationship:

$$\mathrm{CV} = \frac{S}{\bar{\bar{X}}} \times 100 \qquad (2.10)$$

where CV is the coefficient of variation; X-bar is the average long-term rainfall and S is the standard deviation of rainfall

2.2.5.2 Determination of growing season characteristics

Rain-day definition

To determine *Kiremt* onset and cessation dates, a rain-day was defined traditionally for a station as any day it received measurable rainfall (1mm or more). For the delimitation of dry-spells, however, rain-days can be defined less conventionally. Considering crop agriculture in some locations daily potential evapotranspiration may exceed the daily rainfall, thus 1mm rainfall per day seems insignificant amount for crop use, but it does signify the ending of a dry-spell (Sivakumar, 1992). Days not classified as rain-days are considered ‘‘dry days’’, sequences of which are important for defining rainy season cessation and dry-spells. For the study, considering rain amount significance to agriculture, rain day threshold was set to 1mm (onset and cessation determination) and 3mm (dry spell determination) per day as suggested by Reddy (1990) and Segele and Lamb (2005) for Ethiopia.

Onset date determination

Applying onset criteria that performed well in the dry areas to other parts of the study basins may give extremely early and unreasonable onset dates. Therefore, two separate sets of onset criteria were developed, one for the wetter regions that have on average more than 30 rain days in July– August, and the other for dry regions with less July–August rain-days (Segele and Lamb, 2005). Accordingly, for wetter regions: The basic onset date was the first day of the year’s first wet-spell of at least three days totaling 20 mm or more, provided there were no sequences of eight or more dry (<1 mm) days in the subsequent 30 days. For drier regions**:** The basic onset date was defined as the first day of the year’s first wet-spell of at least a one-day rainfall of 10mm or more, provided there were no sequences of eight or more dry (<1 mm) days in the subsequent 30 days. To prevent this criterion giving early onset dates for regions having a bimodal annual rainfall cycle that includes short *Belg* rains before main summer rain (central, and northeastern Ethiopia), only onset dates within two months of the climatological onset date was considered. The criteria have been used by various authors (Barron et al., 2003; Stern et al., 2006; Kassie et al., 2013; Bekele et al., 2016)

Cessation date determination

The end of the growing season is mainly dictated by stored soil water and its availability to the crop after the rainfall stops. Stern et al. (2006) defined the end of the season as the first date on which soil water is depleted and reaches zero. However, this definition was modified when extended dry periods of more than 20 days occurred in mid-season, after which persistent rains returned. To avoid erroneously interpreting such dry-spells as cessation, the above cessation criterion was complemented by the prerequisite that, if rain occurs on more than 2 days in a 30-day period after an extended dry-spell, the search for a cessation date is advanced so that a date satisfying the above basic criterion is determined from the last day of the dry-spell (Segele and Lamb, 2005). For areas such as parts of Omo-Gibe basin, that has comparable mean numbers of rain-days during March–April and July–August, *Kiremt* cessation was defined as the first day of a dry-spell of at least 15 days that occurred after onset. If no such dry-spell occurred by the end of November, then the first day of a post-November 1 dry-spell of at least five days were taken as the cessation date (Segele and Lamb, 2005). The calculation was performed based on a simple water balance, using rainfall, potential evapotranspiration and soil moisture storage capacity. Potential evapotranspiration was determined for the base period using the modified Penman-Monteith method (Allen et al., 1998).

Length of growing period (LGP)

FAO (1996) described the growing period as the period of the year when both moisture and temperature conditions are favorable for crop growth. Determination of LGP was made by subtracting the date of cessation from the date of true onset. Thus, the period between the beginning and ending dates was regarded as the growing period.

2.2.5.3 Dry-spells determination

Different alternative criteria can be used to identify and characterize dry-spells that occurred each year between the determined *Kiremt* onset and cessation (Segele and Lamb, 2005). The study used dry spell criteria with a day or continuous days with daily rainfall amount of less than 3 mm for its agricultural significance. Beginning and ending dates of dry-spells were used to calculate the maximum, average, and total dry-spell lengths for each year under each criterion. Further, to quantify dry-spell likelihood, a simple first order Markov chain model was fitted to determine a probability of dry spell occurrence for 3, 5, 8 and 11 days during the main growing season (Stern et al., 2006).

2.2.5.4 Determination of seasonal water requirement satisfaction index

The spatially explicit water requirement satisfaction index (WRSI) is an indicator of crop performance based on the availability of water to the crop during a growing season (Senay and Verdin, 2003). WRSI is the ratio of seasonal actual crop evapotranspiration (AETc) to the seasonal crop water requirement, which is the same as the potential crop evapotranspiration (PETc).

$$\text{WRSI} = \frac{\sum \text{AET}_c}{\sum \text{PET}_\text{c}} \text{ X } 100 \tag{2.11}$$

where WRSI – is water requirement satisfaction index; AETc – actual evapotranspiration of the crop; PETc –water requirement of the crop

Actual evapotranspiration of a crop (AETc) represents the actual amount of water withdrawn from the soil water reservoir where shortfall relative to water requirement of the crop (PETc) which is calculated by a function that takes into consideration the amount of available soil water (Senay and Verdin, 2003). Water requirement of the crop (PETc) denotes crop specific potential evapotranspiration after an adjustment is made to the reference crop evapotranspiration (PET) by the use of appropriate crop coefficients (Kc). The water requirement of the crop at a given time in the growing season was calculated by multiplying PET by the crop coefficient (Kc). Crop coefficient values define the water use pattern of a crop. Soil water content (SW) was estimated through a simple mass balance equation where the total volume is defined by the water holding capacity (WHC) of the soil in the effective root zone of the crop. Soil water content is the amount of soil water present at a given time step and its value varies from a minimum of 0 to a maximum equal to WHC (mm). Each time step's new SW is obtained after determining the actual extraction by the crop (AETc).

The water requirement satisfaction index was then determined using a water balance approach (Stern et al., 2006). It starts with a value of 100% at the start of the growing season, while water deficit and water excess reduce WRSI. Initial soil water could contribute to the WRSI at the beginning of the season, but such information is often not available. According to Stern et al. (2006), The WRSI decreases in two ways: (1) if there is water surplus of more than 100 mm, then the index is reduced by 3 units (a surplus poses negative influence on the crop performance by 3% for each 100 mm of excess water). (2) if there is a deficit, the index is reduced by the percentage of this deficit in relation to the total water requirements for the season. Values of WRSI between 50-100% imply conditions ranging from severe stress (on the lower end) to conditions with adequate moisture to avoid crop stress. Whereas values of

WRSI below 50% indicate crop failure due to severe moisture stress (Smith, 1992; Martin et al., 2000).

Maize crop with 100 (early maturing), 130 (medium maturing) and 180 days (late maturing) was used to determine the seasonal water requirement depending on the corresponding LGP of each site. Crop coefficient values of maize were derived for each growing stage and linearly interpolated in to daily values using INSTAT software. Published values of Kc for maize (FAO, 1998) are available for critical points in a crop phenology and intervening values for the study, maize Kc values were taken as 0.3, 1.20, 1.20, and 0.35 for the growing stages corresponding to 0-16%, 16-44%, 44-76%, and 76-100% of LGP, respectively.

2.2.5.5 Climate change analysis

Projected changes in rainfall and temperature

Delta changes in mean daily rainfall and daily temperature were computed for near, mid and far century climate relative to the base period using the generated climate data of the climate models. Percent changes were calculated for all agroclimatic indices using (eq. 2.12). Annual and seasonal changes were considered using 30 years of simulated data for each station considered in the study. Delta changes in annual total rainfall and annual mean daily temperature were mapped to show spatial variations in the study areas.

$$\% \Delta = \frac{\text{Proj-Baseline}}{\text{Baseline}} \; X \; 100\% \tag{2.12}$$

where, Proj = projected value; Baseline = Baseline value; Δ= change

Projected changes in growing season characteristics, dry spell and water requirement satisfaction index

The projected climate was characterized using standard agroclimatic indices for the near, mid and far periods and compared with the base period (1981-2010) for any seasonal changes related to rainfed agriculture. The generated daily climate values from the selected models were used to determine the growing season characteristics of the study basins under the changed climate. Standard procedures were employed to determine the agroclimatic indices during near, mid and end century (the procedures are listed in detail under section 2.2.4.2 to 2.2.4.3). The indices were used to infer shifts in main season onset and cessation, changes in potential length of growing period, changes in length and frequency of dry spell occurrences. Similarly, WRSI was calculated in the same way as the baseline condition for the near, mid and far periods (see section 2.2.4.4 for the detail WRSI procedures). Although WRSI requires soil water holding capacity values of corresponding stations to calculate water balance during the future time period, due to unavailability of such data for future scenarios current soil water holding capacity of the corresponding areas were considered. Long-term climate data with a length of 30 years were used for each period. Onset and cessation dates, length of growing period (LGP) and probability of dry-spells occurrences and water requirement satisfaction index were analyzed using INSTAT *v*3.7 plus software.

2.3 Results and Discussions

2.3.1 Rainfall characteristics, trends and variability in the GRVB

2.3.1.1 Rainfall characteristics

The characteristics of precipitation in the GRVB indicate the presence of various agroecology's with different patterns of precipitation. Across the study area, two distinct patterns of rainfall were depicted (Figures 2.2 and 2.3). The first pattern includes areas with bimodal rainfall where *Belg* and *Kiremt* seasons prevail. In these areas, the short rainy season, *Belg*, peaks in April, while the long rainy season, *Kiremt*, peaks in July. In some other areas, bimodal rainfall pattern in which the highest rainfall is received in the months of April (long season) and October (short season) was identified. The second pattern recognized in the study area is the monomodal pattern of rainfall with a long *Kiremt* season that stretches from March through November.

These variations in the study basins may be explained by the geographical position of stations with respect to the equator. Mutai and Ward (2000) for example, discussed spring is the major rainfall period for the near-equatorial regions of extreme southern and southeastern Ethiopia which is associated with the long rainy season of equatorial East Africa whereas the northern and northeastern stations of which receive its monsoon rain start during May and June because of the ITCZ position during that period of time.

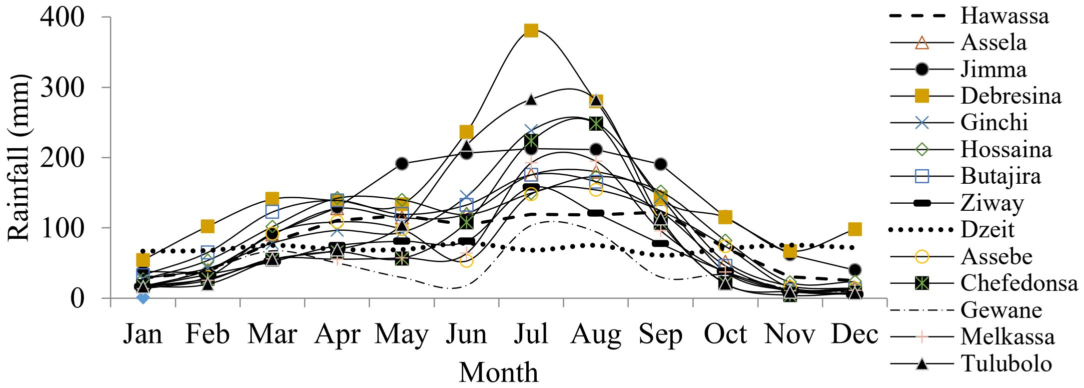


Figure 2.2. Bimodal (*Belg* and *Kiremt*) rainfall distribution of stations in the GRVB.

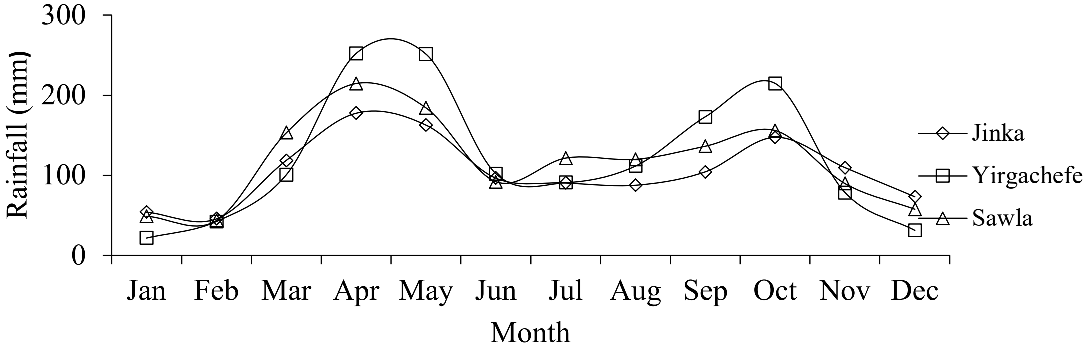


Figure 2.3. Bimodal (long and short season) rainfall distribution in the GRVB.

The long-term annual mean rainfall of the basins varied from 503 mm in the arid parts of the basins to 1890 mm. The main growing season received 59% of the total annual rainfall while the short season contributed to 30% of the total rain received by the basins. Highest main season rainfall was recorded in Jimma (1411 mm) which contributed to 92.5 % of the total annual rainfall received by the station. Debresina (1052 mm) and Tulubolo (900 mm) received the highest main season rainfall next to Jimma. The contributions of the main season rain of these stations respectively are 55 and 75% to the total annual rainfall of the corresponding areas. The lowest main season rainfall was recorded at Gewane (245 mm) which will be challenging to execute rainfed agriculture. Similarly, the short season rainfall also varied in the study basins. The highest values were recorded at Debresina (516 mm) and Yirgachefe (457 mm) while the lowest was at Gewane (188 mm).

2.3.1.2 Rainfall trends

The annual rainfall showed no significant changes during the record period, except at Melkassa where a highly significant ($P \leq 0.01$) increase of 9.88 mm/yr was observed (Table 2.4). The majority of the stations (8 out of 16 stations) showed a non-significant positive trend in the range of 0.66 to 4.25 mm/yr while some stations (7 out of 16) showed a non-significant negative trend ranging from 0.55 to 3.17 mm/yr. Similarly, the main season rainfall showed non-significant trend at all stations in the GRVB, except for Gewane (+ 6.55 mm/yr) and Melkassa (+ 5.57 mm/yr) ($P \leq 0.05$). The most hydro-meteorological time series are characterized by monotonic change in a mean value defined as trend is sometimes observed in such series (Duggal and Sons, 2000).

Table 2.4. Annual and seasonal rainfall trend (mm/yr) in the GRVB during 1981-2010

Station Name	Annual			Main season			Short season		
	Z	Q	P-value	Z	Q	P-value	Z	Q	P-value
Asebeteferi	-0.04	-1.69	0.751	0.17	3.57	0.179	-0.18	-5.71	0.169
Assela	-0.14	-3.17	0.272	-0.13	-2.58	0.321	-0.08	-1.86	0.572
Hawassa	0.04	0.66	0.762	-0.11	-1.45	0.402	-0.07	-1.57	0.621
Butajira	-0.002	-0.55	1.000	0.13	3.42	0.339	-0.12	-4.64	0.357
Chefedonsa	0.03	2.23	0.832	0.08	1.7	0.572	-0.01	-0.25	0.944
Debresina	0.06	4.25	0.672	0.15	7.43	0.256	-0.22	-7.54	0.087
Debrezeit	0.03	0.89	0.859	-0.04	-0.43	0.777	0.01	0.2	0.944
Gewane	0.18	4.03	0.1551	0.41	6.89	**0.001**	-0.29	-3.67	**0.024**
Ginchi	-0.09	-3.0	0.479	0.08	1.85	0.556	-0.20	-4.17	0.126
Hossaina	0.09	3.33	0.524	0.08	1.76	0.551	0.01	0.39	0.944
Jimma	0.11	3.85	0.396	0.14	3.64	0.304	*	*	*
Melkassa	0.40	9.88	**0.001**	0.31	5.57	**0.018**	0.09	1.30	0.509
Sawla	-0.05	-2.22	0.697	-0.13	-2.29	0.339	-0.04	-0.57	0.777
Tulubolo	-0.01	-0.80	0.944	0.05	2.00	0.697	-0.12	-2.33	0.353
Yirgachefe	-0.04	-2.7	0.777	-0.14	-3.08	0.272	-0.06	-2.1	0.646
Ziway	0.13	3.01	0.321	0.05	0.81	0.724	-0.02	-0.4	0.887

*indicates station with one long season, bold P-values indicate significance at 0.05/0.01 alpha level

The result is in agreement with reports from other studies in different parts of the country. For instance, Bekele et al. (2016) reported the *Kiremt* season rainfall exhibiting a non-significant increasing trend in eight out of 12 stations, but three out of 12 showed statistically significant trends in the Awash basin of Ethiopia. Cheung et al. (2008) reported a decline in the *Kiremt* rainfall for watersheds located in the southwestern and central parts of the country, but also their observed changes were not statistically significant for any of the watersheds examined. Few stations in south Ethiopia did show a negative significant trend in annual rainfall (Gebremichael et al., 2014). Similarly, Osman and Sauerborn (2002) also found negative anomalies with *Kiremt* rainfall frequently being lower than the long-term average for the north central highlands of Ethiopia. On the other hand, Kassie et al. (2013) reported a non-significant rainfall trend for the CRV stations, except for one stations out of sixteen.

Despite the absence of significant trends in rainfall patterns, the high inter-annual variability and season to season variation implies a challenge to rainfed agriculture. The declining trend in *Kiremt* rainfall and increase in daily rainfall intensity disadvantages rainfed crop production. Various studies indicated that the amount and temporal distribution of rainfall is generally the most important determinant of inter-annual fluctuations in crop production in Ethiopia and has significant effects on the country 's economy and food production for the last three decades (World Bank, 2006; Bewket and Conway, 2007; Hellmuth et al., 2007; Araya and Stroosnijder, 2011; Conway and Schipper, 2011; Demeke et al., 2011; Kassie et al., 2013; Bekele et al., 2016). The inter-annual and intra-seasonal rainfall variabilities in the GRVB are accompanied by a significant warming trend in temperature, which can add stress to crop growth during periods of already high temperatures.

2.3.1.3 Rainfall variability

To describe the characteristics of the station suitability to rainfed agriculture the amount received by station may not be enough. The coefficient of variation of the annual, main and short season rainfall is portrayed in Table 2.5. The nature of its annual distribution would be equally important. The coefficient of variation (CV%) is an important measure to look at the inter-annual variabilities of rainfall distribution (Bewket and Conway, 2007; Kassie et al., 2015; Bekele et al., 2016).

Table 2.5. Rainfall variability and PCI of selected stations in the GRVB, 1981-2010

Station	Alt.(m)	Annual		Main season		Short season		PCI (%)
		Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	
Asebeteferi	1792	928	25.0	477.3	30.4	329.5	46.4	11.7
Assela	2413	1093.8	14.5	620.2	16.9	372.7	39.2	11.8
Hawassa	1694	969.6	14.2	464.8	23.8	347.7	26.1	10.2
Butajira	2000	1147.7	22.5	597.1	25.2	446.6	42.1	11.2
Chefedonsa	2392	943.1	24.4	682.4	23.0	205.1	55.8	16.5
Debresina	2800	1890.1	25.6	1051.6	34.5	515.8	36.5	11.1
Debrezeit	1900	850.8	14.8	283.1	23.8	282.4	25.9	8.4
Gewane	568	502.9	23.5	245.1	36.9	187.6	45.5	12.6
Ginchi	2132	1177.7	21.6	774.4	23.1	311.4	44.3	13.7
Hossaina	2307	1156.9	17.2	593.6	15.1	437.8	29.7	10.7
Jimma	1718	1525.7	12.7	1410.9	13.7	NS	NS	10.8
Melkassa	1540	814.9	17.1	547.4	18.9	194.7	46.6	15.1
Sawla	1347	1416.3	14.6	551.9	23.7	381.7	32.1	9.9
Tulubolo	2100	1196.9	25.2	899.6	32.1	245.1	40.5	16.7
Yirgachefe	1856	1468.7	24.2	604	29.1	456.6	33	11.7
Ziway	1640	749.1	19.8	437.3	22.3	241.7	43.2	12.5

NS-No short season (monomodal)

The rainfall of stations in the study basins showed both temporal and spatial variabilities. The total annual rainfall of stations showed variability ranging from low to high. According to Hare (1983), coefficient of variation (CV) of stations are classified as low for below 20% CV, high for CV in the range of 20-30% and CV values of more than 30% are regarded as very high variability. The coefficient of variation of the annual, main and short season rainfall ranged from low to very high class (Table 2.5). It can be noted that half of the basins fall under low variability and the other half of the selected stations fall under high variability in-terms of their annual total rainfall. Unlike the annual total rainfall of stations, the seasonal rainfall showed high degree of variability. Accordingly, only 25% of the stations fall under low variability for the main season rainfall. The rest, majority (75%) of the stations showed high (50%) to very high (25%) variability ranges. The short season is very prone to risk for rainfed agriculture that almost all of the selected stations in the basins clearly indicate very high (80%) to high (20%) ranges of rainfall variability.

Similar results were published by Kassie et al. (2013), Gebremichael et al. (2014) and Bekele et al. (2016) for CRV in South Ethiopia and Awash Basin, respectively. The authors indicated a high coefficient of variation (CV% >30) for *Belg* season rainfall than its corresponding *Kiremt* season. Seleshi and Zanke (2004) emphasized the causes of total and seasonal inter-annual variability of precipitation over Ethiopia. They indicated the forward and retreat pace of the African sector of the intertropical convergence zone (ITCZ) and their ending and beginning times vary annually, causing most of the inter-annual variability in rainfall over Ethiopia. The migration of ITCZ is sensitive to variations in Indian Ocean sea surface temperatures that vary from year to year, influencing the characteristics of the season in the region as well as episodes of El Niño Southern Oscillation and La Niña (Dessu and Melesse, 2013). The Precipitation Concentration Index (PCI) values also indicated that in most of the stations, the values were more than 10% (Table 2.5) indicating presence of seasonality in rainfall distribution (Bewket and Conway, 2007; Bekele et al., 2016) in the study basins.

2.3.2 Main growing season characteristics

The agricultural quality of an individual *Kiremt* results from potentially complex interplay among several parameters – the timing of *Kiremt* onset and cessation and the frequency and duration of its dry-spells (Segele and Lamb, 2005). Station based analysis was made to capture the nature, characteristics and spatial variations of main growing season in the Great Rift Valley Basins of Ethiopia.

2.3.2.1 Onset and cessation

Dates of main growing season onset (Figure 2.4) and cessation (Figure 2.5) varied across the representative stations within the great rift valley basins of Ethiopia. Mean potential onset dates ranged from Julian date number 83 to 167 (which is from March 23 at Jimma to June 15 at Gewane). Earlier onset of the main growing season might be associated with the relative position of the station from the equator, where the position of the intertropical convergence zone (ITCZ) roughly reaches the equator during the spring equinox in its northerly migration. Consequently, the southern part of the basin receives the long rains (Mutai and Ward, 2000) in March which describe early onset in those stations. The standard deviation of onset ranged from ± 11.4 to ±32.4 days. The higher standard deviation of the onset date of the seasons implies that patterns could not be easily understood and consequent decisions pertaining to crop planting and related activities will be made with high risk.

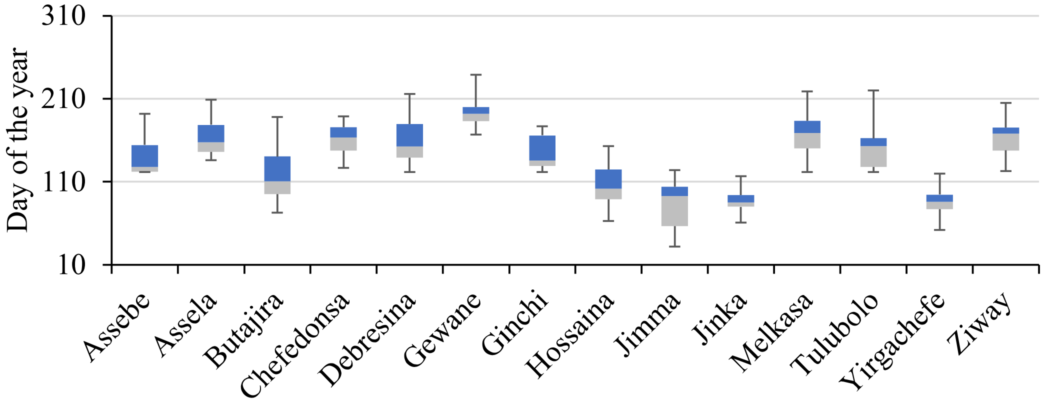


Figure 2.4. Onset date of the main rain season of stations in the GRVB.

Similar reports were also made by Segele and Lamb (2005) in their thorough investigation for climatic variations of Ethiopia. Their results revealed that the mean *Kiremt* onset advances gradually northeastward from southwestern regions. The rains start in early-to-mid March over southwestern Ethiopia and progress northward to cover the western half of the country by mid-June. At the other extreme, the northeastern regions do not receive their first rain until mid-to-late July, with the latest mean onset being over the dry regions of the Rift Valley.

The end of the season is governed by stored soil water and its availability to the crop after the rain stops. Mean dates of cessation varied from Julian date number 222 to 322 (from August 9 to November 17). Unlike the start of the season, the end date did not show variations for the majority of stations considered. However, some stations showed high variability in their cessations of the main growing season (standard deviation up to 64 days at Yirgachefe). Similarly, Assebe, Debresina and Jinka also showed uncertainties in their season cessations. The annual variabilities in predicting end of the season may affect farmers decision to select high yielding long maturing crops.

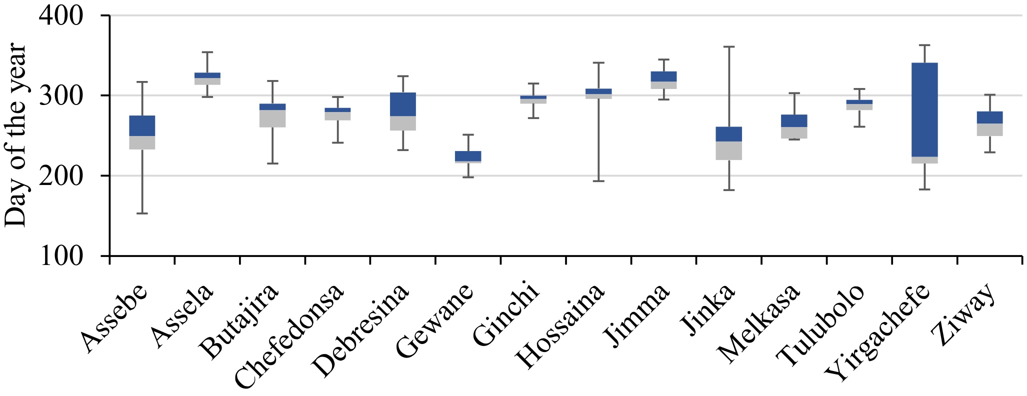


Figure 2.5. Cessation date of the main rain season in the GRVB.

Studies by Segele and Lamb (2005) indicated that different ranges of temporal variability exist in the mean onset and cessation date depending on geographical location of the stations but orographic effects should not be undermined. Cessation variability is reported to be the largest in the southwest, where the onset is earliest, and the smallest in the north and northeast, where the onset is latest and growing season becomes shortest. They also emphasized that within the larger-scale climate system context, the southwestward *Kiremt* retreat is associated with the seasonal-weakening of the eastern Atlantic and western Indian ocean monsoon systems and the southward displacement of the near equatorial trough/ITCZ.

The box and whisker plot indicated the distribution of the potential onset dates and cessation of the main growing season for the recorded 30 years period. The box indicated the distribution of the middle second and third quartiles of 50% of the data, whereas the upper and lower whiskers indicate the distribution of the upper and lower each 25% of data distributions.

2.3.2.2 Length of growing period (LGP)

Length and spatial variations of the growing season

The mean potential LGP of the main growing season ranged from 20 to 236 days (Figure 2.6). The standard deviation of LGP for *Kiremt* growing season ranged from 20 to 45 days. The results revealed high inter-annual variability of LGP, which can be explained by high inter-annual variability in the onset and cessation dates in the season. Similarly, the results of Bekele et al. (2016) indicated early/delayed onset and/or corresponding delayed/early cessation resulted in the annual variation in the duration of the growing season in the Awash basin of Ethiopia. High variability (CV > 20%) in the seasonal rainfall might have resulted in the variability of the main season length of the growing period (Table 4.2).

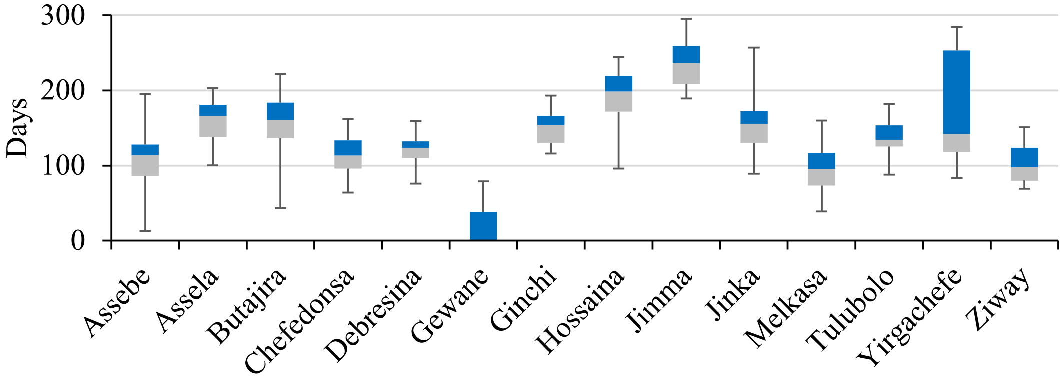


Figure 2.6. Length of growing period (LGP) of selected stations in the GRVB.

The spatial variations in the LGP, dates of onset and cessation characteristics of the main season in the GRVB is indicated in Figure 2.7. Length of growing period clearly show variation ranging from as low as 20 in the arid lowlands of the north east to more than 7 months in the humid and sub humid regions of mid-west parts the study area. The central region of the basin mainly the rift floor did show LGP in a range between 3-4 months during the main season.

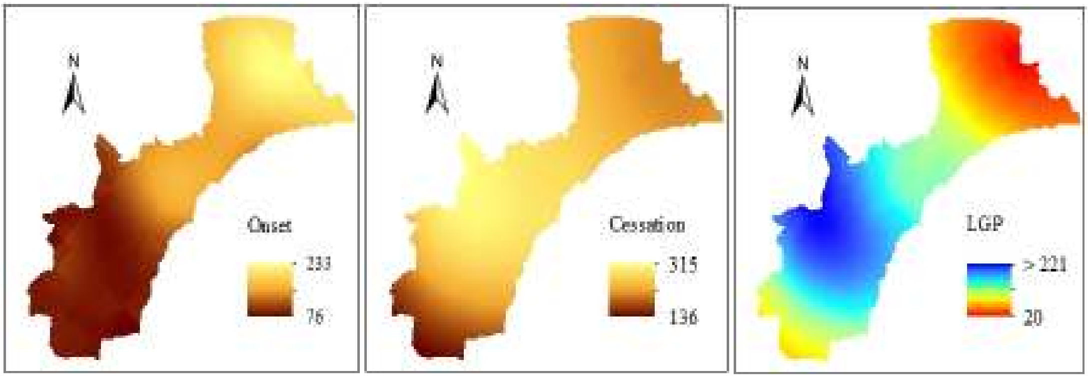


Figure 2.7. Onset, cessation and LGP of main growing season, 1981-2010.

2.3.2.3 Dry spell occurrence during the main growing season

Probability of dry spells for 3, 5, 8 and 11 consecutive days that occurred during the growing season is indicated for selected representative stations of the GRVB in Figure 2.8. The analysis showed that the arid parts of the GRVB like Gewane experienced high probability of dry spell of 3 day (100%) and 5 days (more than 70%) during the main growing season. Humid areas like Jimma showed probability of a dry spell occurrence of 3 days (above 50%) and 5 days (lower than 20%) during the main growing season. The semiarid areas (Melkassa and Ziway) showed a relatively high probability of 3 and 5 days of dry spell in most of the years during the middle of the growing season where Ziway was highly vulnerable in most of the years. Spell length of 8 and 11 consecutive days in the main season happens rarely below 20% regardless of the stations' agroecology. The short season however suffer from long days of dry spell, which makes the season unreliable to rainfed agriculture.

Similar reports by Kassie et al. (2013), indicated that the CRV is characterized by intermittent dry spells with higher probabilities of occurrence during the growing season. Most of the crops cultivated in the CRV are most likely to be exposed to moisture stress. For instance, at Ziway, there is a chance of 26% of getting dry spells of longer than 7 days at the early growth stage of a crop and the probability is higher (92%) during the late development stage of the crop. Studies by Segele and Lamb (2005) and Araya and Stroosnijder (2011) also indicated that dry spells of about 10 days length were among the major causes of crop failure in rainfed farming systems of Ethiopia. The latter authors indicated that 20% of crop failure in drought prone parts of Ethiopia was due to dry spells during the growing season. The increased probability of dry spells at all stations in late August and thereafter might be related to the southward shift of the ITCZ (Araya and Stroosnijder, 2011). On the other hand, Segele and Lamb (2005) indicated that long and consecutive dry spells were strongly related to a major downturn in dew point, abnormally high temperatures, and easterly winds throughout the troposphere beneath a weak tropical easterly jet.

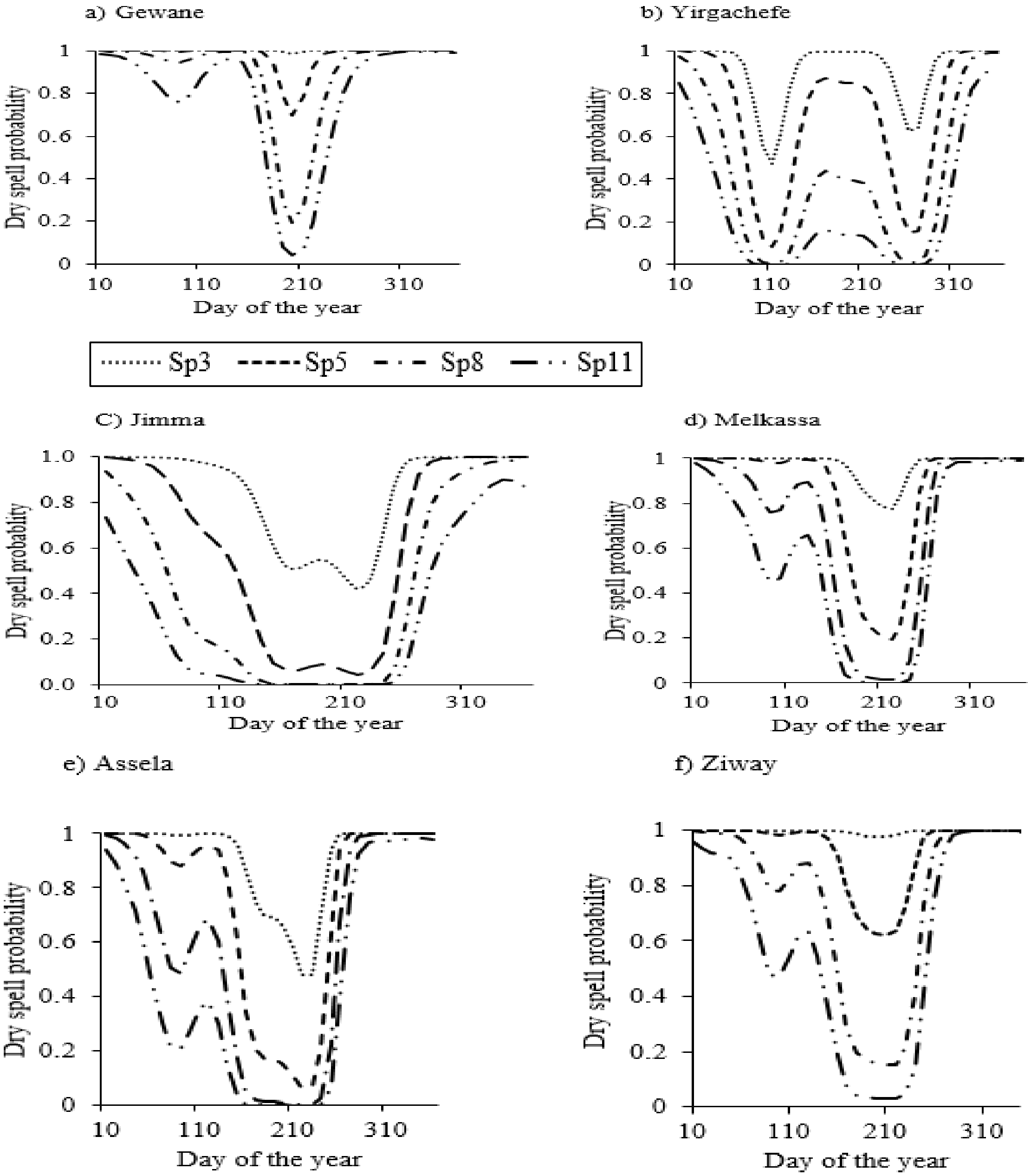


Figure 2.8. Probability of dry spell occurrence of 3, 5 8 and 11 days of selected stations in the GRVB.

Seasonal water requirement satisfaction of the main season

The main seasons performance of water requirement demand and its supply was evaluated for rainfed maize during 1981-2010 period. Seasons performances were analyzed for late, medium and early maturing maize planted under two planting windows (May and June). The results of selected representative stations are depicted in the figure below (Figure 2.9). The semiarid areas of the basins such as Melkassa and Ziway usually suffer from moisture deficit during the growing season. At Melkassa, medium maturing (a) maize planted in May planting window experienced mild moisture deficit (WRSI < 80%) in most of the years (46.7% of the years) than the same maize cultivar planted during June planting window (26.7% of the years).

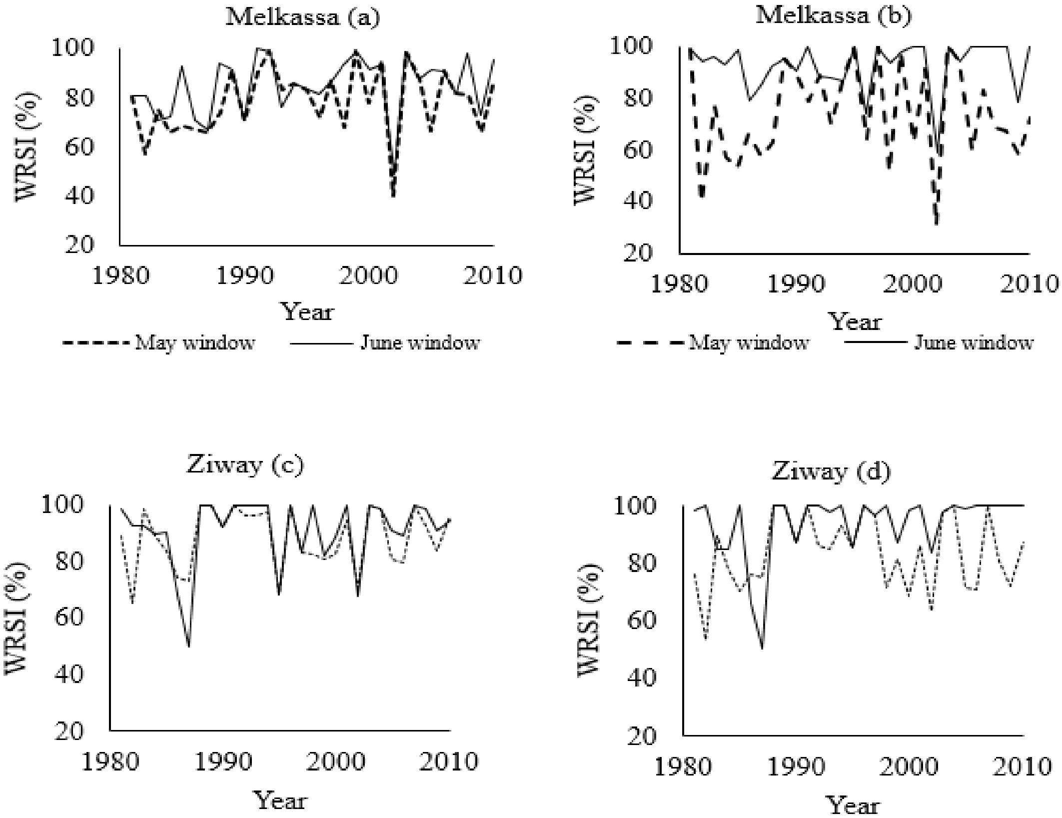


Figure 2.9. Seasonal WRSI for a) medium & b) early maturing maize at Melkassa and c) medium & d) early maturing maize at Ziway.

A seasonal WRSI value less than 50 is regarded as a crop failure condition (Smith, 1992; Martin et al., 2000). Similarly, early maturing (b) maize planted earlier in May (three out of five years) was severely affected by moisture deficit than when it was planted in June at Melkassa, where only 13% of the season satisfy below 80% of the total water requirement. It can also be noted that planting short maturing varieties of maize earlier in the season may cause a complete crop failures or significant yield reductions. In contrast to the results at Melkassa, medium maturing cultivars of maize may benefit, if planting takes place early in the season in May than planting in June at Ziway. However, for early maturing cultivars, the risk of experiencing moisture dificit is higher (WRSI < 80%) for most of the seasons when planting takes place in May (40% of the years) than in June (only 6.7% of the year).

Medium and high rainfall areas, unlike low rainfall areas, experienced very little risk of seasonal moisture deficit during the growing season. An example is displayed in Figure 2.10(a) where a case of "no deficit" was obtained at Assela resulting in a WRSI value of 100, which corresponds to the absence of yield reduction related to water deficit for medium maturing cultivars when planted either at early May or June. The late maturing cultivars in the same location however were impacted by severe moisture deficit in one out of fifteen years leading to complete crop failures, if planted in June than when the planting takes place in May planting window (Figure 2.10(b)).

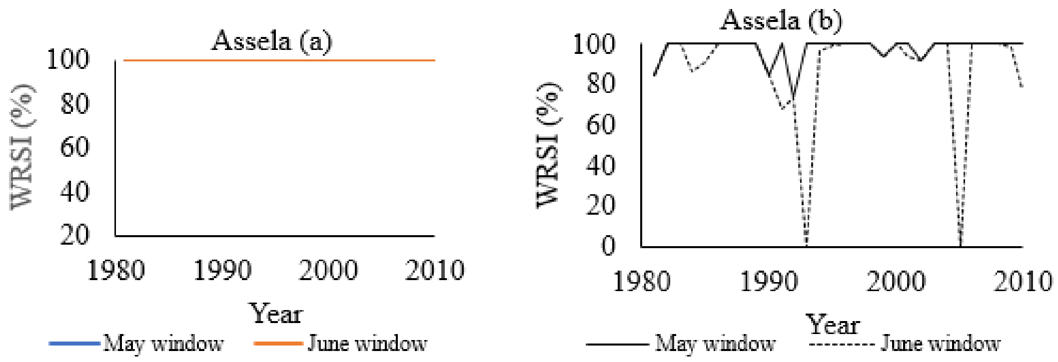


Figure 2.10. Seasonal WRSI of medium (a) and late maturing maize (b) at Assela

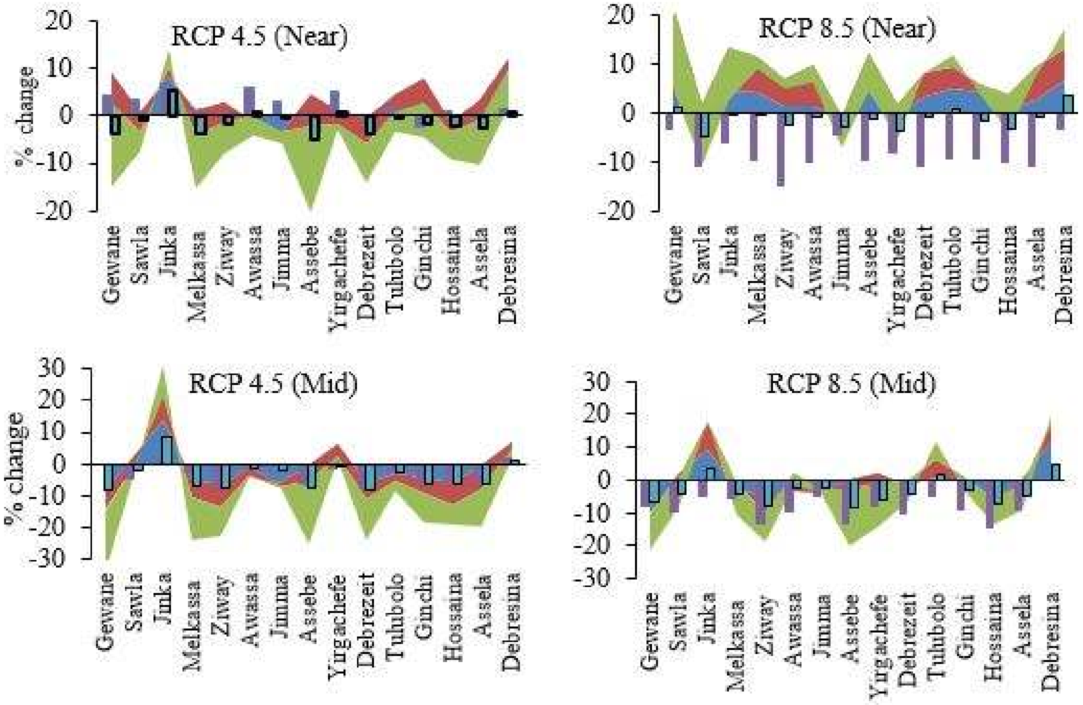
The water requirement satisfaction index calculated for 90-day and 120-day cycled maize cultivars indicated that the effective rainfall available during the growing season was not sufficient for maximum production of the crops in most of the seasons. Kassie et al. (2013)

indicated that crops grown in the CRV, particularly long cycled varieties, experienced water stress during the growing season and farmers need to shift to short cycled crops as long as rainfall is the only source of water for crop production. They further implied the necessity of improved farm management practices to support production of short cycled varieties.

2.3.3 Climate changes in the projected climate scenario

2.3.3.1 Projected changes of precipitation in the GRVB

Projections based on eight GCM-RCM models, with two emission scenarios suggested that the annual and seasonal rainfall will most likely decline in the future of this century relative to the current reference period (1981-2010). Majority of the climate models projected a decline in annual precipitation in the near, mid and far future for most of the stations in the GRVB (Figure 2.11). HaDGEM2-ES_RCA4 projections for example, revealed changes in precipitation ranging from +4.2 to -16% and +3.8 to -18% for near period under RCP4.5 and RCP8.5 emission scenario, respectively. The ensemble means of the model's projections over the basins also indicated declines in precipitation across all periods and emission scenarios considered in this study.



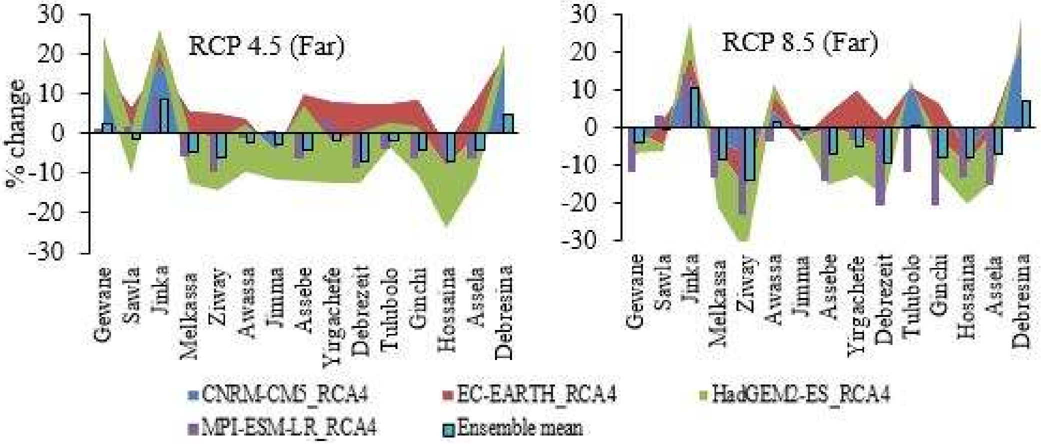


Figure 2.11. Projected changes in annual rainfall in the future period relative to 1981-2010.

The range of projected rainfall changes is presented for Melkassa station in Appendix Table 3 and Appendix Table 4. The change in annual rainfall for RCA4 RCM based simulations (Appendix Table 3) suggest a 6% increase from a single model and RCP (CNRM/RCP4.5) while the rest models and emission scenarios project a decline that range from -2% (by ECEARTH/RCP8.5) to -24% (by HadGEM2-ES/RCP8.5). In similar token, all CLMcom RCM based simulations (Appendix Table 4) yielded a decline in precipitation ranging from -7% (CNRM/RCP4.5) to -25% (HadGEM2-ES/RCP4.5) at the end of this century.

The most relevant months from the point of view of rainfed crop production (i.e. February to September) showed a declining rainfall in most projections for Melkassa (Appendix Table 3 and Appendix Table 4). The *Kiremt* rainfall (June to September) showed an extremely wide range of projected changes from +312% (by HadGEM2-ES_RCA4/RCP8.5) to -42% (by MPI-ESM_RCA4/RCP8.5). Similarly, the rainfall changes for the *Belg* season (February to May) is also extremely wide from +86% (by HadGEM2-ES_RCA4/RCP8.5) to -84% (by HadGEM2-ES_RCA4/RCP4.5).

The variation in rainfall projection by the selected models were indicated by prior studies on African climate (IPCC, 2013; Otieno and Anyah, 2013; Rowell, 2013; Jury, 2015; Bhattacharjee and Zaitchik, 2015). All reports indicated, for the same period, multi-model GCM studies of African climate as a whole and of selected sub-regions consistently showed that GCM/RCMs differ dramatically in their representation of precipitation climatology and variability, even within the period of modern observations. This lack of consensus projects onto simulations of future climate (Bhattacharjee and Zaitchik, 2015). In agreement with our findings, several research results reported that there exists a wide model disagreement in climatically complex regions such as the Greater Horn of Africa (GHA), parts of southern Africa, and the Sahel (Williams and Funk, 2011; Biasutti, 2013; Otieno and Anyah, 2013).

Although models vary in the magnitude and direction of rainfall changes, considerable models projected increasing rainfall amount during the main season while the net annual change showed a declining rainfall in each of the model and emission scenario considered in this study, except CNRM_RCA4/RCP4.5. Studies indicated that a decline in 10% of seasonal rainfall from the long-term average translates to 4.4% decrease in the countries food production (von Braun, 1991), which might signal that decline in precipitation would challenge the rainfed crop production unless proper adaptation measure is in place.

Projection of future rainfall suggested that both annual and main season rainfall are most likely to decrease for most of the stations and climate scenarios. Our result agrees with past research findings on future rainfall projections for Ethiopia (Arndt et al., 2011; Kassie et al., 2015). A decrease of *Kiremt* rainfall by 4 to 20% for the central rift valley was reported during the mid-period under RCP4.5 and RCP8.5 emission scenario with respect to 1980-2009 period (Kassie et al., 2015). Similar result was also reported by Arndt et al. (2011) indicating that the *Kiremt* rainfall will decline by 20% and the *Belg* rainfall will decline by 5-6% by 2080s relative to the 1960-1990 period.

2.3.3.2 Projected changes of temperature in the GRVB

Unlike precipitation, the entire basin may experience increases in temperature in the near mid and far century as compared to the base period (Table 2.7). Almost all of the considered models projected an increase in temperature consistently across the stations and periods. Under each future period, higher positive changes were projected for all stations under RCP8.5 than the corresponding RCP4.5 emission scenarios. The ensemble of models by RCP suggested Melkassa might be warmer by 0.76 to 0.91 ºc by RCP4.5 and RCP8.5, respectively in the near period. Similarly, Assela is projected to warm by 0.77 to 0.92 ºc in the near future relative to the base year under RCP4.5 and RCP8.5, respectively.

Table 2.6. Changes in temperature (°C) in the GRVB relative to 1981-2010

GCM_RCM	Near (2011-2040)			Mid (2041-2070)			End (2071-2100)		
	Melkassa	Assela	Jimma	Melkassa	Assela	Jimma	Melkassa	Assela	Jimma
RCP4.5									
CNRM_RCA4	0.65	0.63	0.48	1.38	1.28	1.04	1.85	1.73	1.41
ECEARTH_RCA4	0.68	0.74	0.62	1.37	1.5	1.23	1.71	1.89	1.56
HadGEM2-ES_RCA4	0.92	0.95	0.7	1.76	1.8	1.32	2.29	2.34	1.79
MPI-ESM_RCA4	0.78	0.78	0.63	1.47	1.51	1.21	1.71	1.73	1.41
Ensemble mean	0.76	0.77	0.61	1.49	1.52	1.2	1.89	1.92	1.54
RCP8.5									
CNRM_RCA4	0.79	0.74	0.62	1.94	1.8	1.45	3.5	3.22	2.54
ECEARTH_RCA4	0.77	0.82	0.71	1.89	2.09	1.73	3.2	3.54	3.02
HadGEM2-ES_RCA4	1.09	1.12	0.9	2.5	2.53	1.95	4.24	4.29	3.32
MPI-ESM_RCA4	0.97	1	0.86	2.15	2.18	1.86	3.83	3.86	3.19
Ensemble mean	0.91	0.92	0.77	2.12	2.15	1.75	3.69	3.73	3.02

On the other hand, GCM_RCM combinations differ in the magnitude of change under both emission scenarios and periods, although they consistently projected increases in temperature across stations and periods. HadGEM2-ES_RCA4 model projected the highest increase across all periods for each location than the rest models while CNRM_RCA4 projected the least relative to the other models. The different models projected a wide range of temperature increases for the representative stations under each RCP. The projections at Melkassa for instance showed an increase from +0.65 ºc (by CNRM_RCA4) to +0.95 ºc (by HadGEM2-ES_RCA4) in the near period which will likely to further escalate during mid (1.38 to 1.76 ºc) and far (1.85 to 2.29 ºc) periods under RCP4.5 emission scenario. In similar token, the worst-case scenario (RCP8.5) was projected to increase Melkassa temperature in the range between +0.77 ºc (by ECEARTH_RCA4) to 1.09 ºc (by HadGEM2-ES_RCA4) in the near term and again will likely double in the mid (+ 1.89 to + 2.5 ºC) as well as in the end (3.2 to 4.24 ºC) centuries using the same set of models. It was observed from the analysis that all agroecology will likely warm in the future but the change of temperature between two consecutive periods will be higher for the semi-arid lowlands (Melkassa) than that of the humid regions (Jimma) under both emission scenarios

To understand the spatial variation of changes in temperature across the basins, HadGEM2-ES_RCA4 model results were mapped for the two emission scenarios and the three future periods relative to the base period (Figure 2.12). Temperature is projected to rise from +0.7 to +1.25 °c under RCP4.5 to +0.9 to +1.6 °c under RCP8.5 across the basin in the near future. The temperature likely to escalate in the basin in the mid and far periods where in some parts of the basin, the changes may likely rise up to +4 to +6 °c. Even the modest emission scenarios projected an increase in temperature ranging from +2.6 (mid) to +3.4 °c (far period) which can adversely affect agriculture and water resources and in-turn directly or indirectly affecting millions who dwell in the basins. In the future, all the models agreed that temperature will increase across all the stations considered in the study. The study suggested the warming trend will continue and the annual temperature is expected to increase in the range of 2.5-5.1°C averaged over RCPs by the end of this century.

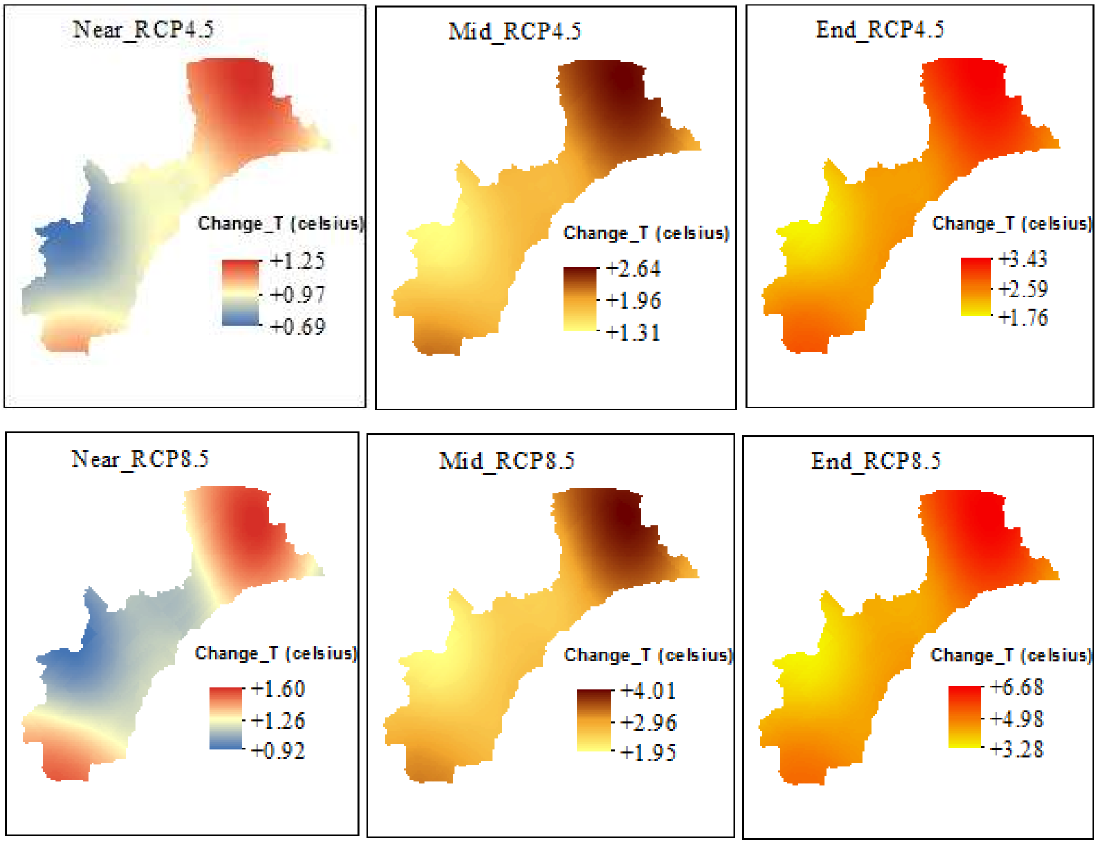


Figure 2.12. Changes in annual average temperature (°C) as projected by HadGEM2-ES_RCA4 RCM in near, mid and end of century relative to the baseline.

This result is consistent with reports for varying national, regional and global scales. For global scale projection, the Fifth IPCC assessment synthesis report suggested an increasing trend of temperature in the range of 1.4 to 4.8°C by the end of the century under RCP4.5 and RCP8.5 emission pathway (IPCC, 2014). Regional and sub regional warming was also indicated for East and Central Africa by about +2 °C during 2050s (Kwena et al., 2018). Similarly, for Ethiopia, NMA (2007) reported that the annual temperature is expected to increase in the range of 2.7 to 3.4°C by the 2080s compared to the 1961-1990 base period. The highest increases are indicated in the lowland areas which are currently characterized by extremely high temperatures in the basin. The climate change is expected to worsen the situation in the currently hotter regions in the future while the relatively warmer and cooler regions might suffer by the unprecedented warming in the future.

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2.3.3.3 Projected changes in growing season characteristics

Three selected stations were used to represent three major contrasting agroecology to understand the impacts of the future climate on the seasonal characteristics of the basin. Melkassa represents the warm sub-moist lowlands, Assela represents tepid moist highlands, whereas Jimma represents tepid humid highlands of the study basins. Changes in LGP is usually governed by the relative changes in onset and cessation of the season. The relative changes in onset and cessation of the main growing season is indicated for near period simulated by various RCMs and RCPs (Figure 2.13). The different models simulated a decline of LGP consistently for warm sub-moist lowlands (Melkassa) ranging from -5.66 to -25.5%, whereas the models varied in their projections from an increase of +3.5 to a decrease by -16.4% for tepid moist high lands (Assela) during near century with respect to the base period. The tepid humid highlands of the GRVB however did not show any significant changes in LGP during the same period (Figure 2.14).

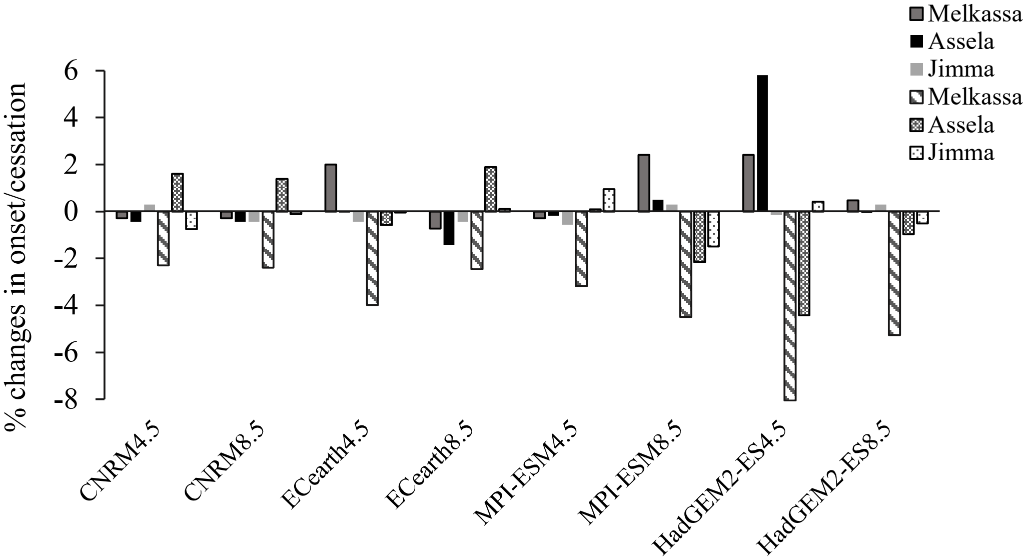

Figure 2.13. Simulated changes in onset (solid bar) and cessation (patterned bar) during 2011-2040 relative to 1981-2010 period.

The results of temporal changes of LGP simulated by HadGEM2-ES_RCA4 model for example revealed that the warm sub-moist lowlands of the basin (Melkassa) exhibit the highest declining trend in the length of the main season (from -17.9% (RCP8.5) to -22.9% (RCP4.5) in the near future than the rest agroecology while Jimma showed a slight decline in LGP ranging from 5.8% (RCP4.5) to 6.8% (RCP8.5) for the same period. On the other hand, Asella exhibited an increase in LGP ranging from +2.24% (RCP4.5) to +5.1% (RCP8.5) during the near period. The simulations also suggested Melkassa will highly be affected by shortening in its effective LGP averaged over RCPs by -27.5% and -25.9% for mid and end of century, respectively. Tepid moist highlands such as Assela might show an insignificant increase of LGP (by 0.2%) during the mid while a decreasing LGP (by -4.3%) at the end of century. The high rainfall belts of the basin (Jimma) on the other hand, might be affected in the order of -5.5% and -8% by mid and end of century, respectively.

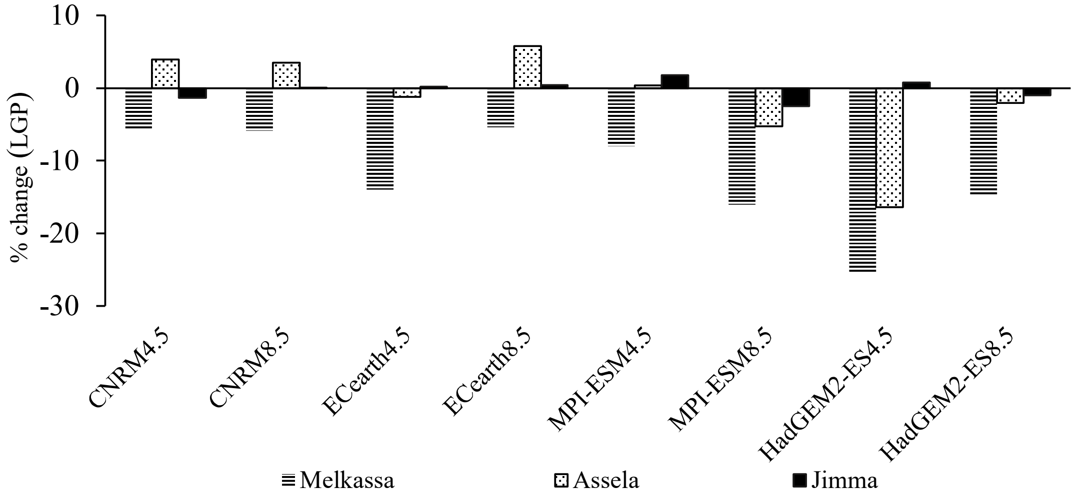

Figure 2.14. Changes in length of growing period during 2011-2040 relative to 1981-2010 period.

Associated with the declining trends in main season rainfall, the length of growing season of GRVB is also expected to be shortened. The result obtained falls within the ranges of values simulated by (Kassie et al., 2015) for stations in the CRV. The author indicated that increases in temperature in the CRV resulted in a shortening of growing period by 14–33% across the climate change scenarios during mid period. Similarly, Region wise studies by Thornton et al. (2006) reported that there will be little to moderate reduction in the length of the growing period (< 20%) in much of the regions across Africa including Ethiopia and in other parts the reduction will be more severe (>20%). The results imply that those regions that are currently aridic will become more aridic and hence agriculture will become more challenging under the changing climate.

Suitable agroclimatic zones for growing economically important perennial crops are estimated to significantly diminish in Africa, largely due to the effects of rising temperatures (Läderach et al., 2010; Eitzinger et al., 2011; Läderach et al., 2011). Under warming scenario, by midcentury suitable agroclimatic zones that are currently classified as very good to good for perennial crops may become more marginal, and what are currently marginally suitable zones may become unsuitable; the constriction of crop suitability could be severe in some cases. Movement of perennial crops to higher altitudes would serve to mitigate the loss of suitability at lower altitudes but this option is limited.

2.3.3.4 Dry Spell occurrence under climate change

Dry spell frequency

The probability of dry spell occurrence of length 7 days and more was analyzed for contrasting agroecology in the GRVB for the future periods during the main season (June-September) (Table 2.8). The result indicated that different agroecology behaved differently in the direction and magnitude of dry spell probability changes that might happen in the future due to climate change.

Table 2.7. Changes in total number of dry spell length of consecutive 7 days and more for future period with respect to 1981-2010 simulated by HadGEM2-ES_RCA4 model

Period/RCPs	Melkassa			Assela			Jimma		
	1mm	3mm	5mm	1mm	3mm	5mm	1mm	3mm	5mm
Dry spell*	28	52	72	9	18	42	1	12	24
Near_RCP4.5	0	+3.9	+14	+22	+39	+12	+100	-8.3	-4.2
Near_RCP8.5	0	+3.9	+14	+22	+28	+7	+300	-8.3	+17
Mid_RCP 4.5	0	+3.9	+14	+22	+39	+14	+100	-8.3	-13
Mid_RCP 8.5	0	+3.9	+14	+22	+33	+9.5	+100	-8.3	-4.3
End_RCP 4.5	0	+3.9	+14	+22	+39	+12	+300	-8.3	+17
End_RCP 8.5	+50	+3.9	+14	+22	+39	+17	+100	-8.3	-13

*Total number of occurrences of dry spell length of 7 days and more during 1981-2010 *Kiremt* season

The number of dry spell lengths of more than 7 days during the main growing season might increase in the future periods for Melkassa (by 4 and 14% under 3 and 5 mm dry day threshold levels, respectively for all periods and RCPs) and Assela (+28 to +39% under 3 mm dry day threshold level and +7 to +17% for 5mm threshold level). The humid parts of the basin such as Jimma, except for the 1mm threshold dry day and few emission scenarios, showed a decrease in the occurrence of such dry spells (by -8.3 for 3 mm dry day threshold) while a decrease from -4 to -13% to an increase of +17% during Near/RCP8.5 and End/RCP4.5 under 5 mm dry day thresholds which might positively contribute to agricultural activities. The increased occurrences of dry spells during the main season in the future might likely pose a serious challenge on the dominant rainfed based farming systems, especially in the semiarid lowlands such as Melkassa.

Dry Spell length

The projected declining rainfall amount will further extend the dry spell length during the main growing season in most of the stations considered in the future (Table 2.9). The relatively drier parts of the GRVB such as Melkassa showed the highest mean dry spell length of 8 days (range from 3 to 13days) within the growing season. The relatively cooler regions did show a mean dry spell length of 5 days (2 to 8 days) at Assela and 4 days (2 to 6 days) at Jimma in their main growing seasons.

Table 2.8. Maximum dry spell length of main season (by HadGEM2-ES_RCA4 model)

Period_RCP	Mean length of maximum dry spell during *Kiremt* season using 3mm rainfall threshold (30 years/period mean ± SD)					
	Melkassa		Assela		Jimma	
	Mean ± SD	% Δ	Mean ± SD	% Δ	Mean ± SD	% Δ
Base period	8.38 ± 4.7	-	5.43 ± 3.3	-	3.93 ± 1.7	-
Near_RCP4.5	8.39 ± 4.7	+0.12	5.67 ± 3.3	+4.42	3.97 ± 1.7	+1.02
Near_RCP8.5	8.39 ± 4.7	+0.12	5.53 ± 3.3	+1.84	3.97 ± 1.7	+1.02
Mid_RCP 4.5	8.39 ± 4.7	+0.12	5.67 ± 3.3	+4.42	3.93 ± 1.7	0
Mid_RCP 8.5	8.39 ± 4.7	+0.12	5.59 ± 3.3	+2.95	3.93 ± 1.7	0
End_RCP 4.5	8.39 ± 4.7	+0.12	5.67 ± 3.3	+4.42	3.97 ± 1.7	+1.02
End_RCP 8.5	8.39 ± 4.7	+0.12	5.72 ± 3.3	+5.34	3.93 ± 1.7	0

HadGEM2-ES_RCA4 based simulations revealed that slight increases in dry spell length may happen in the study basins under near, mid and far periods and two emission scenarios. The relative changes in the increase in dry spell length are higher for currently cooler sub humid and humid environments such as Assela (1.84 to 5.34%) and Jimma (from 0 to 1.02%). The semi-arid lowlands such as Melkassa however did not show considerable changes in the mean dry spell lengths (0.12% under all periods and RCPs) as compared to the reference period.

2.3.3.5 Water requirement satisfaction index (WRSI) under changed climate

The average seasonal water requirement satisfaction index for early (90-day), medium (120-day) and late (180-day) maturing maize varieties at Melkassa, Assela and Jimma with their corresponding WRSI values of the future period simulated by HadGEM2-ES_RCA4 was depicted in Table 2.9. In the future, WRSI value for early and medium maturing maize varieties will likely decline across periods and emission scenarios for Melkassa.

Consequently, early maturing variety of maize might face moisture deficit in the main season ranging from -4.62 (near) to -6.15% (mid & end of century) under RCP4.5 while from 0 (near) to -7.69% (end of century) under RCP8.5 scenario. Similarly, WRSI for medium maturing maize declines in a range between -7.35% (near) to -8.82% (end of century) under RCP4.5 and from -1.47% (near) to -10.29% (end of century) under RCP8.5 emission scenarios.

Table 2.9. Changes in WRSI for early, medium and late maturing maize

Period_RCP	Melkassa		Assela		Jimma	
	Early	Medium	Medium	Late	Medium	Late
Baseline (%)	65 ± 18	68 ± 12	92 ± 8	84 ± 15	99 ± 1	95 ± 7
	% changes in WRSI with respect to baseline (1981-2010)					
Near_RCP4.5	-4.62	-7.35	-5.44	-9.53	-1.01	-1.05
Near_RCP8.5	0	-1.47	-1.08	-2.38	-1.01	2.11
Mid_RCP 4.5	-6.15	-7.35	-6.52	-10.71	0	0
Mid_RCP 8.5	-4.62	-5.88	-4.35	-8.33	-1.01	-1.05
End_RCP 4.5	-6.15	-8.82	-5.44	-10.71	-1.01	-3.16
End_RCP 8.5	-7.69	-10.29	-7.61	-13.1	0	0

The relatively high yielding cultivar (medium maturing maize) seems to be much highly affected by the future periods which implicates the challenge towards feeding the ever-increasing population. Similarly, the sub humid agroecology also showed a decline in WRSI for medium and late maturing maize varieties during the future periods as compared to the reference period under both emission scenarios. The decline in WRSI of medium maturing maize might range from -5.44 (near & end) to -6.52% (mid) under RCP4.5 and from -1.08 (near) to -7.61% (end of century) under RCP8.5. Similarly, the late maturing variety will likely suffer from considerable moisture deficit in the main season at Assela in the future periods. WRSI was projected to decline in a range from -9.53 (near) to -10.51% (mid and end of century) under RCP4.5 while under RCP8.5 the decline might be in the range -2.38 (near) to -13.1% (end of century). The humid regions of the basins on the other hand, will likely be insignificantly affected by the changing climate.

2.4 Conclusions

Annual and seasonal rainfall variability, declining rainfall amount, variability and reduction in the length of the growing seasons, prolonged in-season dry spells as well as insufficient and dwindling seasonal moisture availability in the baseline and projected periods coupled with increasing temperature suggest a pressing challenge for rainfed crop production in the region. The degree of risk however showed variation across agroecology and climate change scenario where arid and semiarid areas are being affected and might highly likely be further affected in the future. Shortened growing seasons due to a late start of rainfall and early cessation hampers soil preparation and exposes crops to increased terminal moisture stress during grain filling, reducing crop yields. In addition, it could affect production of well adapted medium and late maturing cultivars in the absence of supplementary irrigation. The increasing temperature on the other hand will increase the rate of evapotranspiration and crop water requirements, adding to the currently frequent water stress of crops in the relatively drier parts of the GRVB. Rainfed crop production in the region, which is already impacted by the current climate variability, is likely to be further challenged with future climate change. As a consequence, specific impact -based adaptation strategies are essential to reduce the vulnerability of rainfed crop production in the area.

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CHAPTER THREE

Climate Induced Yield Level, Variability and Yield Gap of Maize in the Semi-arid Central Rift Valley of Ethiopia

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3 Climate Induced Yield Level, Variability and Yield Gap of Maize in the Semi-arid Central Rift Valley of Ethiopia

Abstract

Soil moisture and nutrient availability are the two key edaphic factors that determine crop yield and are directly or indirectly affected by climate variability and change. The study examined climate induced yield variability, gap and resource use efficiency of maize during 1981-2010 main growing season in the Central Rift Valley (CRV) of Ethiopia. Pearson correlation test was employed to see the relationship between climate variables and yield. Coefficient of variation (CV) was used to analyze annual yield variability. Decision Support System for *Agro-technology Transfer cropping system model (DSSAT-CSM) was used to simulate yield for the study period. The result indicated that maize grain yield was strongly ($P<0.01$) and positively correlated with seasonal rainfall ($r=0.67$ at Melkassa and $r = 0.69$ at Ziway) in the CRV while day temperature affected grain yield negatively ($r= -0.44$) at Ziway ($P<0.05$) during the simulation period. Variation in total seasonal rainfall at Melkassa and Ziway explained 44.9 and 48.5% of the variation in yield respectively, under optimum nutrition. Following variation in rainfall, high yield variability (CV=23.5%, Melkassa and CV=25.3%, Ziway) was observed for unlimited nutrient simulation than the corresponding nutrient limited simulation (CV=16%, Melkassa and 24.1%, Ziway) in the base period. The observed farmers' yield was 72, 52 and 43% of the researcher-managed, water-limited and potential yield of the crop, respectively, indicating wide maize yield gap in the region. The study revealed rainfed crop production in the CRV is prone to yield variabilities due to its high dependence on seasonal rainfall and nutrient level, hence adopting options that can improve water availability and nutrient use efficiency would be crucial for crop production in the area.*

Key: Climate variability, water productivity, nutrient use efficiency, crop model

3.1 Introduction

Meeting societal demand for food is a global challenge as research estimates indicate that global crop demand will increase by 100 to 110% from 2005 to 2050 (Tilman et al., 2011). Others predict food demand will double within 30 years (Glenn et al., 2008), equivalent to maintaining a proportional rate of increase of more than 2.4% per year. At least, a doubling of agricultural yields is required during the coming decades in economies where majority of the population depends on smallholder rainfed farming for their livelihoods. Falkenmark and Rockstrom (2004) concluded that, in fact, a triply green revolution is required to achieve food security in the major food insecure hotspot of the world (sub-Saharan Africa, South Asia and parts of South-East Asia). These are hydroclimatic regions subjected to extreme rainfall variability, water scarcity and a large dependence on green water flows, i.e., soil moisture in the root zone from infiltrated rainfall that contributes to evapotranspiration flow in rainfed farming systems.

Sustainably meeting such demand is a huge challenge, especially when compared to historical cereal yield trends which have been linear for nearly half a century with slopes equal to only 1.2 to 1.3% of 2007 yields (FAO, 2009) and the inevitable presence of climate related risks. A major challenge is thus to reverse trends of soil fertility depletion and soil desiccation in the highly variable climate conditions. There is an emerging consensus that Eastern Africa, particularly Ethiopia, is one of the most vulnerable regions regarding the impacts of climate variability and change (Slingo et al., 2005; Boko et al., 2007; Thornton et al., 2011). Several studies on precipitation and temperature changes indicated that the African continent is now warmer than it was 100 years ago and the rainfall exhibited higher inter-annual and intra-seasonal variability (Boko et al., 2007; Cooper et al., 2009; Rosell, 2011). Climate variability over the last three decades of the 20th century resulted in droughts and famine in several countries of Africa (Conway and Schipper, 2011; Dixit et al., 2011).

Ethiopia is among the most vulnerable countries in Africa due to its great reliance on climate sensitive sectors, particularly agriculture (Thornton et al., 2006; World Bank, 2006; Hellmuth et al., 2007; Conway and Schipper, 2011; Rosell, 2011). 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). Climate variability, particularly rainfall variability, and associated droughts have been the major causes of food insecurity and famine in Ethiopia (Conway, 2000; Seleshi and Zanke, 2004; NMA, 2007; Conway and Schipper, 2011; Rosell, 2011). For instance, Seleshi and Zanke (2004) reported that the worst famine in Ethiopian history was the result of failure of the main rainfall season, which resulted in reduction of the GDP by 9.7% and agricultural outputs by 21% (World Bank, 2006).

The Central Rift Valley (CRV) of Ethiopia is a typical example of such regions where rainfall variability is commonly affecting crop production (Kassie et al., 2014; Ademe et al., 2020). Few studies indicated huge yield gaps between farmers' and potential yield levels in the area (Kassie et al., 2014; Getnet et al., 2016) due to climate variability and poor resource management. To feed the ever-increasing population and narrow the yield gap in the study area, it is highly desirable to devise options to increase our production level. The country cannot further expand its cropland, as grazing lands have already been gradually converted into cropland, and currently there is little scope for further expansion in crop area (Getnet et al., 2014b). Hence, the focus should be on increasing productivity and improving resource use efficiency (RUE) (Getnet et al., 2016) through a better understanding of climate and biophysical resource base as well as the socioeconomic–institutional context in which local farming systems operate.

Quantitative understanding of temporal and spatial variation in actual and potential crop productivity is lacking (Getnet et al., 2016) and information on yield gaps is only partially available for part of the CRV, and based on limited actual yield data (Kassie et al., 2014). To quantify long term potential yield differences, yield variability and resource use efficiency due to climate variability, nutrient management and their interaction, in areas with limitations in actual field/experimental data Researchers usually employ modelling approach (Jones et al., 2003; Kassie et al., 2014; Getnet et al., 2016). Crop models are generally very important tool to understand long term productivity and resource use efficiency of the cropping system under several input management scenarios, sites and climate conditions (Jones et al., 2003). Therefore, this study aimed at providing up-to-date estimates of climate variability effects on the current level of maize yield, yield gap and resource use efficiency to identify possibilities of producing more with the available resources in efficient manner.

3.2 Materials and Methods

3.2.1 Crop model used and its description

Crop models are powerful tools to assess the risk of producing a given crop in a particular soil-climate regime and to assist in management decisions that minimize the risk of crop production. Crop models integrate knowledge from different disciplines and provide researchers with capabilities for conducting simulation experiments to supplement actual experiments (Jones et al., 2001)

Decisions Support System for Agro-technology Transfer-Cropping System Model (DSSAT-CSM) model is widely used to simulate crop production under different climate change scenarios. DSSAT-CSM is a software package that contains a number of process-based, mechanistic and management oriented crop modules (Jones et al., 2003). 'CERES-maize' is one of the various models embedded in DSSAT to estimate cereals growth and development. The CERES-maize, hereafter referred to as DSSAT, simulates crop development and growth, and the partitioning of assimilates to various plant parts as a function of environmental factors such as soils, weather and crop characteristics. Phenological development and growth of a crop are specified in DSSAT by cultivar-specific genetic coefficients (Hoogenboom et al., 2004). DSSAT consists of soil water, nitrogen balance and the recently incorporated soil phosphorus sub-modules.

The soil water module simulates changes in soil water content across soil layers due to infiltration, soil evaporation, vertical drainage, unsaturated flow and root water uptake processes on daily time step (Jones et al., 2003). The nitrogen module simulates soil nitrogen balance processes such as mineralization, immobilization and nitrogen leaching. The model also simulates phosphorus in plants and soils based on integrated processes between i) inorganic phosphorus present in the soil in three pools, labile, active and stable; ii) organic phosphorus present in two pools, active and stable; iii) plant phosphorus present in roots, shoots, shells and seeds (Daroub et al., 2003). The study used the improved and up-to-date version of DSSAT-CSM v4.7 with improved application programs for seasonal and spatial analysis that asses the environmental impacts associated with fertilizer and nutrient management, climate variability and climate change, which make it the preferred model for this study.

The performance of DSSAT was tested for a range of soil and climatic conditions in various parts of the world and used in the environments of Sub-Saharan Africa including Ethiopia (e.g. (Wafula, 1995; Rötter et al., 1997; Hengsdijk and Van Keulen, 2002; Jones and Thornton, 2003; Thornton et al., 2009; Cairns et al., 2013) and in the Central Rift Valley of Ethiopia (Kassie et al., 2014; Kassie et al., 2015; Liben et al., 2018). Appendix Table 5 presents the modelling approach of DSSAT (CERES-Maize) in describing main crop growth and development processes.

3.2.2 Crop model input datasets

3.2.2.1 Soil data

Soil profile data for each location were obtained from published sources (Ayalew et al., 2015; Kassie et al., 2015 ; Liben et al., 2018) and the hydraulic limits such as lower limit (LL), drained upper limit (DUL) and saturation, drainage coefficients and runoff curve number were generated based on the measured soil properties using the DSSAT internal pedo-transfer functions as discussed by Jones et al. (2003) (Table 3.1). For model initialization, initial soil physico-chemical characteristics of each soil horizon were determined before planting following standard procedures. Two composite soil samples were analyzed for each soil depth. The laboratory analyses for ground and sieved samples included: particle size distribution by Bouyoucos hydrometer method (Van Reeuwijk, 1992); pH in 1:2.5 soil:water ratio after the soil suspension was equilibrated at 25 ± 2 °C (Houba et al., 1989); organic C by Walkley and Black wet digestion method (Houba et al., 1989); total Kjeldahl N (Houba et al., 1989); available P (Olsen et al., 1954); and exchangeable cations by ammonium acetate extraction (Van Reeuwijk, 1992).

3.2.2.2 Crop and management data

Crop and agronomic management data and cultivar information were collected from on-station and on-farm N and P trials previously conducted by Melkassa Agricultural Research Center of the Ethiopian Institute of Agricultural Research during 2010-2017 cropping seasons. Supplementary data were also collected from published sources (Tadesse and Kim, 2015; Liben et al., 2018). Open pollinated variety of Maize variety, Melkassa-2 (ZM-521) adapted to 1200 to 1700 m elevation, was used as test crop (Table 3.1). The net plot area was 9 m^2, with inter-row spacing and intra-row spacings of 0.75 and 0.25 m respectively. The cultivar was released in 2004 by Melkassa Agricultural Research Center and is widely grown in the moisture stressed areas of the CRV (Bogale et al., 2011; Abate et al., 2015; Tesfaye et al., 2015).

Table 3.1 General agronomic information for phenology and grain yield of maize cultivar

Agronomic information	Melkassa-2 (ZM-521)
Altitude (m.a.s.l)	1200-1700
Rainfall (mm)	600-800
Days to anthesis (days)	66
Days to silking (days)	67
Days from planting to maturity (days)	130
Plant height (cm)	170-190
Spacing between rows (cm)	75
Spacing between plants (cm)	25
Plant population density (plants m^{-2})	5.33
Recommended fertilizer rate (N/P kg ha^{-1})	64/20
Potential yield (Mg ha^{-1})	8

Source: Bogale et al., 2011

The N fertilizer source was Urea split (2/3rd) applied at planting and 1/3rd at the 5-leaf stage, whereas Triple superphosphate (TSP) was used as a P source. Band application of fertilizers was made near the root zone at 5 mm depth. Tillage was employed according to the local practice by tilling three times using oxen drawn “maresha” plow (Melesse, 2007). The first and second tillage were, respectively, done in the first and second week of June at both sites while the third tillage was done at planting time. Planting was carried out from the last week of May to mid-July at both locations.

3.2.2.3 Weather data

Daily measured weather data of Melkassa (1981-2010) and Ziway (1984-2010) for the present climate, hereafter referred to as baseline period, were obtained from the National Meteorological Agency of Ethiopia (http://www.ethiomet.gov.et) and Melkassa Agricultural Research Centers’ Agrometeorology department. The collected weather data include:

rainfall, temperature (Tmax and Tmin) and solar radiation in a daily temporal resolution. Data quality was priorly ensured and published by Ademe et al. (2020) and the details are provided under chapter 2 section 2.2.1.1.

3.2.3 Data Analysis

3.2.3.1 Crop model evaluation

Model initialization

Soil profile properties by depth including lower soil water limit, drained soil water upper limit, saturated upper limit, and soil growth factors were calculated for Melkassa and Ziway soils using DSSAT 4.7 CSM based on the measured soil profile data (Table 3.2) following Saxton and Rawls method as described by Gijsman et al. (2002). A generic approach suitable for site specific soil organic carbon (SOC) pool initialization based on climate, soil type, and management history was applied to create site-specific SOC fractions (Porter et al., 2010; Basso et al., 2011; Liben et al., 2018). Initial conditions were set separately for Melkassa and Ziway sites under maize monoculture cropping system using the observed crop residue and soil information measured at the start of the actual experiments. The DSSAT-CENTURY 4.7 was used to set the initial SOC fractions.

The model was run using 30 years daily weather data obtained from nearby stations and with the measured soil profile information. The model simulations were for field history of previously cultivated soil under poor management with maize monoculture. Locally recommended maize plant density (5.33 plants/ m^2) and recommended N and P fertilizer rates (69-20 kg NP ha^{-1}) for Melkassa and Ziway sites were used as indicated in Debelle et al. (2001). The model was executed with the iterative procedure described in Basso et al. (2011) until predicted SOC reflected the measured SOC of the soil profiles at the start of the actual experiment for the Melkassa and Ziway soils. The predicted SOC fractions were then used to initialize the model for the intended simulations.

Statistical Indices for model evaluation

Models that performed well in some location should be evaluated before using them elsewhere. Site-specific calibration and evaluation of model performance is thus a precondition for using models for other locations than they were developed (Jones et al., 2003; Kassie et al., 2015; Liben et al., 2018). The main objective of model evaluation is to adapt the model parameters to local conditions (e.g. soil types and weather conditions) to gain a good overall agreement between simulated and observed values (Kassie et al., 2015;Tesfaye et al., 2015). Since the DSSAT model was priorily calibrated for Melkassa-2 maize variety in the lowland maize growing regions of Ethiopia (Tesfaye et al., 2015), it can be used after evaluation of the model performance for the study area conditions.

The experimental data for model validation were derived from N and P-fertilizer experiments on station and on-farm trials during 2010-2017 at Melkassa and Ziway. The model validation was made from different set of fertilizer trials with fertilizer rates of varying levels. The model validation involved checking the model performance across seasons and across different levels of fertilizer rates. The model was evaluated for its seasonal performance using five years phonologic and yield data derived from treatment of local applied fertilizer rate (23-20 NP kg ha^{-1}) during 2010-2015 experimental seasons. Consequent validation of model performance was also undertaken for a single year at Melkassa involving the recommended N rate (69 kg N ha^{-1}) while five P rates (10, 20, 30, 40 and 50 kg P ha^{-1}) were used. A control plot without application of both N&P was also included in the experiment for nutrient use efficiency calculation purpose. The evaluation was made using measured data for days to emergence, days to anthesis, days to physiological maturity, grain yield and total above ground biomass.

Performance of the models was evaluated comparing the deviation between observed and simulated values. Statistical indicators such as the root mean square error (RMSE), normalized RMSE (nRMSE), index of agreement (d), mean error (ME), Pearson correlation coefficient (r) and coefficient of determination (R^2) were employed. The root mean square error (RMSE) (Eq 4.1), measures the average magnitude of the estimated errors with lower RMSE values indicating greater central tendencies and generally smaller extreme errors (Wallach, 2006). The normalized RMSE (nRMSE) (Eq 4.2) gives a measure (%) of the relative difference of simulated versus observed data, and the simulation is considered excellent with nRMSE < 10%, good if between 10–20%, fair if between 20–30%, and poor if equal or greater than 30% (Wallach, 2006). The index of agreement (d) (Eq 4.3) determines the degree of agreement between the predicted and their respective observed values and d = ~1 is desirable (Willmott, 1982; Wallach, 2006). The mean error (ME) (Eq 4.4) estimates the average generated error and a positive and negative ME show that the generated data were generally underestimated and overestimated, respectively. In addition, the Pearson correlation coefficient (r) (Eq 4.5) was used to evaluate how well the generated data corresponds to the observed data (Wallach, 2006). For the statistical evaluation of DSSAT performance, both water and nutrient limited simulations were done. The nitrogen and phosphorus sub-routine of DSSAT model was turned-on and N & P-limited and high N & P treatments were simulated. Small values of RMSE were considered good, whereas d-values and r close to 1 were considered as indicators for good performance of the DSSAT model.

$$\mathrm{RMSE}= \left(\frac{\sum(\mathrm{Yi}\text{-}\mathrm{Zi})}{\mathrm{n}}\right)^{0.5} \tag{4.1}$$

$$\mathrm{nRMSE} = \frac{100\ \mathrm{X}\ \mathrm{RMSE}}{\hat{\mathrm{Y}}} \tag{4.2}$$

$$\mathrm{d} = 1\text{-}\ \frac{\sum(\mathrm{Yi}\text{-}\mathrm{Zi})^2}{\sum\left(|\mathrm{Zi}\text{-}\hat{\mathrm{Y}}|+|\mathrm{Yi}\text{-}\hat{\mathrm{Y}}|\right)^2} \tag{4.3}$$

$$\mathrm{ME} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Yi}\text{-}\mathrm{Zi}) \tag{4.4}$$

$$\mathrm{r} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Yi}\text{-}\hat{\mathrm{Y}})(\mathrm{Zi}\text{-}\hat{\mathrm{Z}})}{\sqrt{\left[\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Yi}\text{-}\hat{\mathrm{Y}})^2\right]\left[\sum_{\mathrm{i}=1}^{n}(\mathrm{Zi}\text{-}\hat{\mathrm{Z}})^2\right]}} \tag{4.5}$$

where: Yi is measured value, Zi is simulated value, n is the number of observations, and Ŷ and Ẑ are the average of measured and simulated values, respectively.

3.2.3.2 Analysis of yield level, variability and gap

Yield level analysis

The simulation was done for two sites (Melkassa and Ziway) which represent rainfed maize production areas in the CRV. Following evaluation of the DSSAT model, a multi-year simulation with historical weather data (1981-2017 at Melkassa and 1984-2017 at Ziway) were carried out to analyze yield level, variability and gaps. The planting date within a planting window (April 15-July 7) was triggered when at least, four day rainfall of 40 mm or more was achieved (Kassie et al., 2015). Initial soil water contents were set to 50% of the water holding capacity at the start of the simulation after it was adapted from Kassie et al. (2014) for the study area condition.

Three levels of yields, namely potential, water-limited and input and water limited yields were simulated. Potential yield is the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled. Therefore, the potential yield is limited by climate conditions (temperature, solar radiation, CO_2 concentration) and plant genetic characteristics (Kassie et al., 2014). The water-limited yield, which is also known as water-limited yield potential, is additionally influenced by rainfall and soil water characteristics on that of the potential yield conditions. The third representing low input systems with both nutrient and water limitations where varying levels of nutrients and soil water characteristics (under rainfed and non-water stress conditions) affect crop production.

Yield variability analysis

For the baseline climate, the inter-annual variability of simulated yields was evaluated using the coefficient of variation (CV) and computed using equation (Eq 4.6).

$$CV=\frac{S}{X} * 100\% \tag{4.6}$$

where CV is the coefficient of variation; X is the average long-term yield and S is the standard deviation of yield. The CV was used to compare the long-term variation of yields to that of individual years.

Yield gap analysis

Yield gap analysis involves quantifying the differences between simulated potential yield and farmers' yield levels and identify those factors responsible for the yield differences (Lobell et al., 2009; Van Ittersum et al., 2013; Kassie et al., 2014; Getnet et al., 2016). The references for calculating yield gaps are yields under optimum management (no nutrient stress) which are potential yields under irrigation conditions or water-limited yield under rainfed conditions (Van Ittersum and Rabbinge, 1997).

Although maize is predominantly grown under rainfed conditions in the study sites, there comes a strong urge to use irrigation in the future. Accordingly, we used the simulated water-limited yield and potential yield as a reference to calculate current yield gaps and differences in yield due to varying levels of management and input usages. To capture management effects on yield differences, we included researcher managed fields (experimental yields) under rainfed condition with nutrient level more or less similar with farmers local application rate (23-20 kg NP ha^{-1}) (Spielman et al., 2011).

In case of African smallholder agriculture, Tittonell and Giller (2013) suggested that the concept of yield gaps can be meaningful when, at least, two main components of yield gaps are distinguished: (i) the gap between water-limited and average farmers‘ yield and (ii) the gap between best yields attained in farmers‘ fields and average farmers' yields. Accordingly, we calculated three types of yield gaps: (1) the gap between simulated water-limited yield and average farmers' yield, (2) the gap between simulated potential yield and average farmers' yield and, (3) the gap between researcher managed trial yield and average farmers' yield. We quantified gaps for each individual year and used the average to define the yield gap for each study site.

Kassie et al. (2014) defined average farmer yield as yield levels achieved with current conventional farming practices, often including low or no external inputs. Average yield data of a minimum 5 recent years are required to define a meaningful yield gap for a given study area (Hochman et al., 2013; Van Ittersum et al., 2013). The average yields in the yield gap calculation were based on nine years data collected from Central Statistical Agency (CSA) dataset for the cropping seasons 2007/08 to 2015/16 (www.csa.gov.et). Researcher managed yields were used from field trials conducted by Melkassa Agricultural Research Center (EIAR) under rainfed condition and local fertilizer application rate (23-20 NP kg ha^{-1}) (Spielman et al., 2011) from 2010-2015 while simulated yields in the same scenario were supplemented for years with no data (2007-2009).

3.3 Results and Discussions

3.3.1 Soil physico-chemical characteristics of the experimental sites

The soil physical and chemical properties of soils at the experimental sites are depicted in Table 3.2. The soil analysis result revealed that physically the texture of the experimental soils of both sites is generally loam, which is suitable for crop agriculture. Across depths, clay and silt are the dominant fractions at Melkassa. The sand fraction at Ziway, on the other hand, was higher in the subsurface than in the surface layer and, hence, the dominant soil textural class varied from loam at the surface to sandy loam at the subsurface layers. The bulk density value showed increments with soil depth and was in the normal range for agricultural soils. Owing to the relatively higher clay and silt contents in the subsurface layer, the water content at both field capacity and permanent wilting point was slightly higher in the same than those at the surface layer at both locations. The total available water holding capacity of the upper 100 cm of the soil showed variations across locations and ranged from moderate (170 mm/m) at Ziway to high (370 mm/m) at Melkassa (Landon, 1991). Variations in the total available water contents across the study sites could explain observed yield differences in the area.

Table 3.2. Selected properties of Melkassa and Ziway soils used in DSSAT simulations

Depth	LL*	DUL	SAT	BD	Clay	Silt	OC	TN	P	pH	CEC
cm	$cm^3\ cm^{-3}$			$g\ cm^{-3}$	(%)				$mg\ kg^{-1}$		$cmol_c\ kg^{-1}$
Melkassa											
15	0.09	0.34	0.39	1.19	20.1	45.2	1.06	0.12	17.3	7.3	33
30	0.19	0.34	0.39	1.23	19.4	47.1	1.04	0.16	12.4	7.5	32
60	0.16	0.35	0.40	1.24	19.2	49.3	1.03	0.21	10.1	7.6	34
100	0.19	0.35	0.40	1.25	18.3	51.3	1.01	0.2	7.4	7.8	34
200	0.21	0.38	0.43	1.24	18.5	51.1	1.01	0.16	6.6	7.9	34
Ziway											
20	0.20	0.39	0.49	1.25	26.2	45.8	1.2	0.45	13.3	7.9	24.6
60	0.16	0.38	0.50	1..26	15.3	41.6	1.2	0.38	9.2	9.1	16.8
105	0.28	0.41	0.45	1.28	16.1	46.1	1.1	0.24	7.6	9.9	10.3
150	0.25	0.32	0.37	1.28	1.1	45.7	1.03	0.21	1.82	9.8	1.21

*LL: lower soil water limit; DUL: drained soil water upper limit; SAL: saturated upper limit; BD: bulk density; OC: organic carbon; TN: total N; P: P-Olsen; and CEC: cation exchange capacity.

Soil organic carbon, which is a key soil fertility indicator was low based on ratings of Landon (1991) at both locations and the amount decreased with depth. Ziway soil showed a slightly higher organic carbon content than Melkassa. The low organic matter content of soils of both sites resulted in low total nitrogen content at both locations and depths. However, owing to the slightly higher amount of organic matter content at Ziway site, total nitrogen measured also showed a slightly higher value than Melkassa site. Based on ratings of Landon (1991), organic carbon is in a low range at both sites while total nitrogen was found to be in the low range at Melkassa and moderate at Ziway. Generally, the soils at both sites can be categorized under high P fertility soils at the surface layer and decreased with depth. The pH of the soil, which governs nutrient availability, falls under slightly alkaline to very high alkalinity ranges in the study locations (Landon, 1991). At Melkassa, the pH value falls from slightly alkaline on the surface layer to highly alkaline in the subsurface layers. Under such pH ranges, there is an increasing liability of deficiency of micronutrients. at the same trend with soil depth was observed at Ziway, which could be detrimental to phosphorous and boron availability (Landon, 1991). Cation exchange capacity (CEC), which is a measure of potential fertility of the soil, ranged from high (Melkassa) to medium (Ziway) (Landon, 1991) which indicates the soils considerable potential for crop production given application of fertilizers.

The physico-chemical characteristics of soils of the study sites indicate variations in some of the pertinent soil parameters for optimum crop production. Considering the soil textural class and bulk density values of the study locations, it can be inferred that such soils do not restrict root growth and hence are ideal for plant growth and suitable for crop production (Landon, 1991). The moderate water holding capacity of Ziway soils coupled with low seasonal rainfall of the area could be detrimental for crop production. Low organic carbon and total nitrogen content of the soils in the area suggest huge requirements of organic residues and inorganic nitrogen addition for sustainable crop production in the area. Likewise, dominance of strong alkaline pH of the experimental soil could affect nutrient availability such as phosphorous and micronutrients and thereby deter crop production unless soil amendments and fertilizer are applied. In general, the soils of the study area could be very suitable for crop production with a considerable soil management action in place.

3.3.2 Crop model evaluation

Model evaluation with the calibrated cultivar parameters provided good agreement between simulated and observed values of crop phenology and yield components for all seasons at both locations (**Error! Reference source not found.**). Days of emergence were simulated with no deviation at both locations, except for a single year with a 1-day deviation. Dates of anthesis, however, were simulated with a deviation of 1 to 10 days at Melkassa and within 2 to 5 days deviations at Ziway during the 5-year validation periods. Dates of physiological maturity were simulated with a deviation of 4 to 7 days (Melkassa) and 4 to 9 days (Ziway) for Melkassa-2 maize variety.

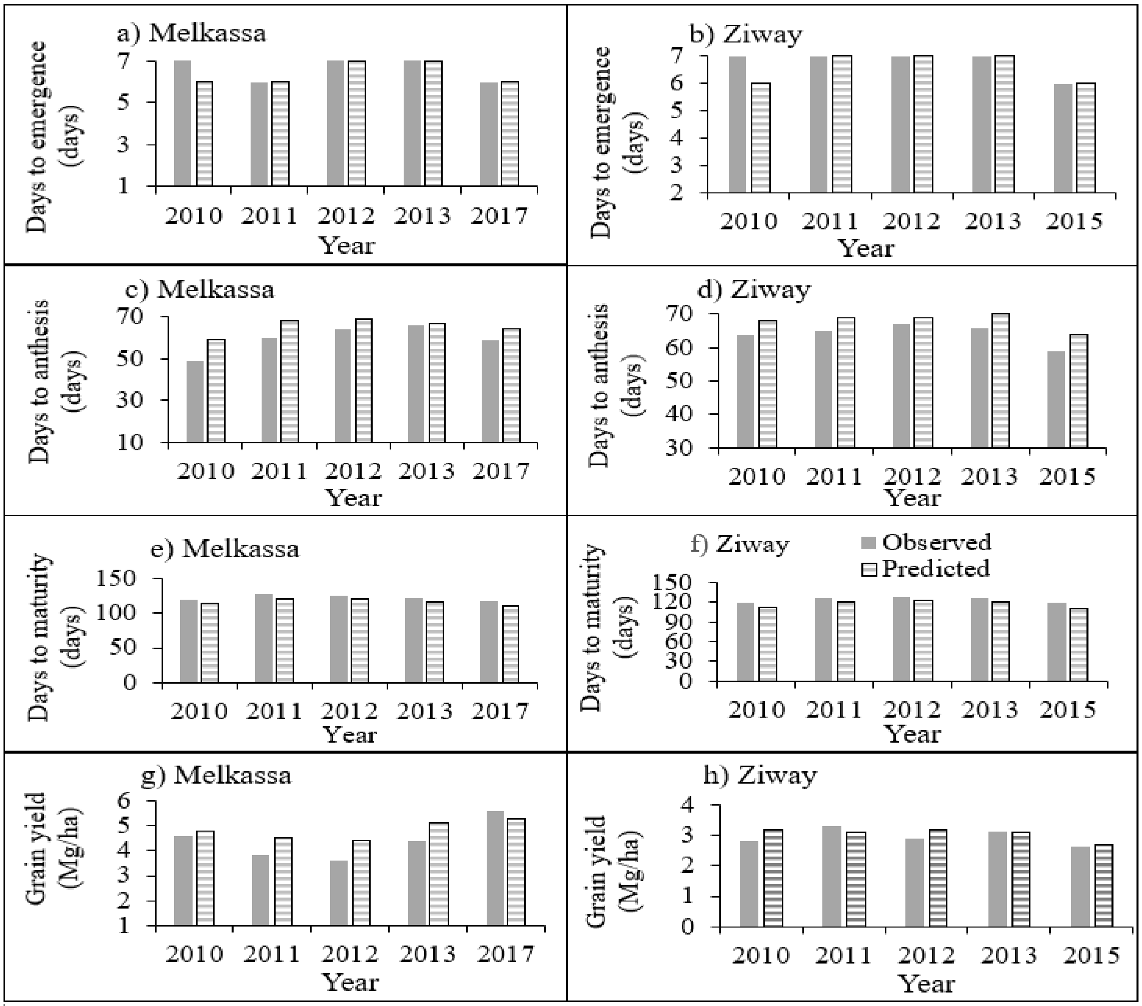


Figure 3.1 Observed vs. simulated days to emergence (a & b), days to anthesis (c & d), days to maturity (e & f) and maize grain yield (Mg/ha) (g & h) for Melkassa-2 maize variety.

Simulated versus observed grain yield and total aboveground biomass were used to validate model performance under varying level of fertilizer rate at Melkassa. The responses of the different fertilizer rates were captured by the model in a good agreement especially for grain yield while above ground biomass was poorly captured (Figure 3.1). The model strongly predicted grain yield for the varying level of P application (Table 3.3 under Validation for fertilizer rates section). A very strong correlation (r=0.996) and index of agreement (d=0.93) close to one, mean error (ME=0.02 Mg/ha) and root mean square error (RMSE=0.08 Mg/ha) close to zero were observed between simulated and predicted maize grain yield. The model, however showed poor performance in predicting aboveground biomass as compared to grain yield under the different levels of P application (Figure 3.2).

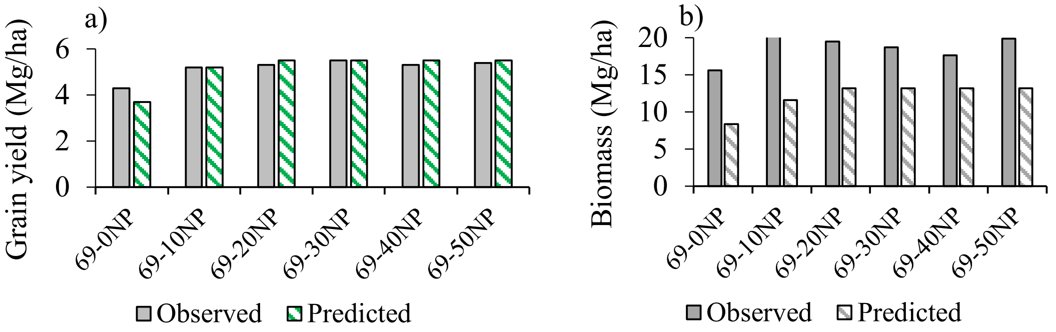


Figure 3.2. Observed vs model predicted grain yield (a) and aboveground biomass (b) of maize under different levels of P application during 2017 (Melkassa).

The good agreement between simulated and observed grain yield was also indicated by low values of the RMSE (0.37 Mg/ha at Melkassa, 0.15 Mg/ha at Ziway), a close-to-one index of agreement (0.93 at Melkassa, 0.86 at Ziway) and a high degree of correlation (0.91 at Melkassa, 0.87 at Ziway) and corresponding high coefficient of determination (83% at Melkassa, 76% at Ziway) (Table 4.3). In general, comparison of model simulated water-limited yield and researcher managed on-farm trial yield for the period 2010-2017 showed a very good agreement whereby high simulated yields had also relatively high on-farm trial yields in the same years (**Error! Reference source not found.**). However, the simulated yield in most cases were higher than on-farm trial yield as shown by statistically negative mean error (ME) values at both locations (Table 3.3). This might be attributed to the yield reducing factors since on-farm trials yield used for the comparison were not absolutely free from the effects of yield reducing factors (e.g. pests, disease, weeds, etc), whereas in model assumptions such factors are perfectly controlled and the management was optimal.

The DSSAT cropping system model adequately simulated measured values for the variables tested under the recommended N and different P rates in the CRV of Ethiopia. For instance, grain and biomass yield and crop phenology at both locations were simulated with index of agreement close to one and with nRMSE < 10% (Table 3.3), wherein the simulation is considered excellent (Wallach, 2006). The model slightly overestimated maize grain yield and aboveground biomass, though the predictions were acceptable. The results of model validation also indicated DSSAT model was able to simulate yields with a considerable accuracy while aboveground biomass for the different P rates was under simulated for all P rates considered.

Table 3.3. Simulations vs observed traits statistics for model evaluation

Validation for seasons	n	r	R^2	ME	RMSE	nRMSE	d
Melkassa							
Days to emergence (days)	5	0.67	0.44	0.2	0.47	7.1	0.96
days to anthesis (days)	5	0.90	0.81	-5.8	3.2	5.4	0.92
Days to maturity (days)	5	0.96	0.93	5.2	8.2	6.0	0.9
Grain yield (Mg ha^{-1})	5	0.91	0.83	-0.54	0.37	8.4	0.93
Aboveground biomass (Mg ha^{-1})	4	0.73	0.53	-3.6	1.14	13.3	0.80
Ziway							
Days to emergence (days)	5	0.61	0.38	0.2	0.4	5.9	0.93
days to anthesis (days)	5	0.96	0.92	-3.8	1.02	1.6	0.91
Days to maturity (days)	5	0.93	0.87	6.6	5.8	4.3	0.91
Grain yield (Mg ha^{-1})	5	0.87	0.76	-0.66	0.15	5.1	0.86
Aboveground biomass (Mg ha^{-1})	4	0.90	0.81	-1.4	0.74	9.1	0.93
Validation for fertilizer rates (Melkassa)							
Grain yield (Mg/ha)	6	0.99	0.97	0.02	0.08	1.54	0.93
Aboveground biomass (Mg/ha)	6	0.69	0.47	6.5	1.43	7.7	0.35

* N, number of data pairs used; r, Pearson correlation coefficient; R^2, coefficient of determination; ME, mean error; RMSE, root mean square error; nRMSE, normalized root mean square error; d, index of agreement.

Performance of DSSAT model in simulating different N rates was reported in different studies (Thornton et al., 1995; Matthews et al., 2002) for Africa and for the CRV areas (Kassie et al., 2014; Liben et al., 2018). However, we couldn't find studies to compare our result for the different P rates in our condition for the fact that unlike N sub module, P sub-module was recently embedded to DSSAT model. In general, it can be concluded that the model precisely simulated yield and other phenological parameters for the recommended N and P levels (69-20 kg NP ha^{-1}) during the evaluation period in the CRV. Therefore, the model can well be used to simulate N and P management in the variable climate of the Central Rift Valley of Ethiopia.

3.3.3 Current yield level, variability and gap

3.3.3.1 Relationships of climate and maize grain yield in the CRV

The correlation analysis between simulated water-limited yield and growing season rainfall, maximum temperature, minimum temperature and solar radiation had Pearson correlation coefficient values (r) of 0.67, 0.3, 0.1 and 0.1 at Melkassa and 0.69, -0.44, -0.1, -0.2 at Ziway, respectively (Table 3.4). Under no nutrient limitation, grain yield was strongly and positively correlated with seasonal rainfall at both locations ($P \leq 0.01$) while increments in day temperature negatively affected grain yield ($P \leq 0.05$) at Ziway during the simulation period. Among the climate variables considered, variations in seasonal total rainfall explained 44.9 and 48.3% of the variations in yield during the analysis period was at Melkassa and Ziway, respectively. Next to variations in seasonal rainfall, variabilities in day temperature at Ziway accounted for 19.6% of the variations in grain yield. Increased day temperature by a unit seems to reduce grain yields which could pose a critical challenge in the future maize production in the area under warming future scenarios.

Table 3.4. Pearson correlation coefficient (r) of simulated maize grain yield with seasonal climate variables during the baseline period

Seasonal climate variables	Melkassa			Ziway		
	r	p-value	R^2	r	p-value	R^2
Seasonal rainfall	0.669**	0.0001	0.449	0.69**	0.000	0.483
Maximum temperature	0.304	0.1025	0.0924	-0.44*	0.014	0.196
Minimum temperature	0.093	0.6237	0.099	-0.07	0.692	0.01
Solar radiation	0.090	0.6353	0.008	-0.15	0.416	0.024
Seasonal evapotranspiration	0.816**	0.0001	0.665	0.87**	0.0001	0.752

** highly significant at $P \leq 0.01$; * significant at $P \leq 0.05$

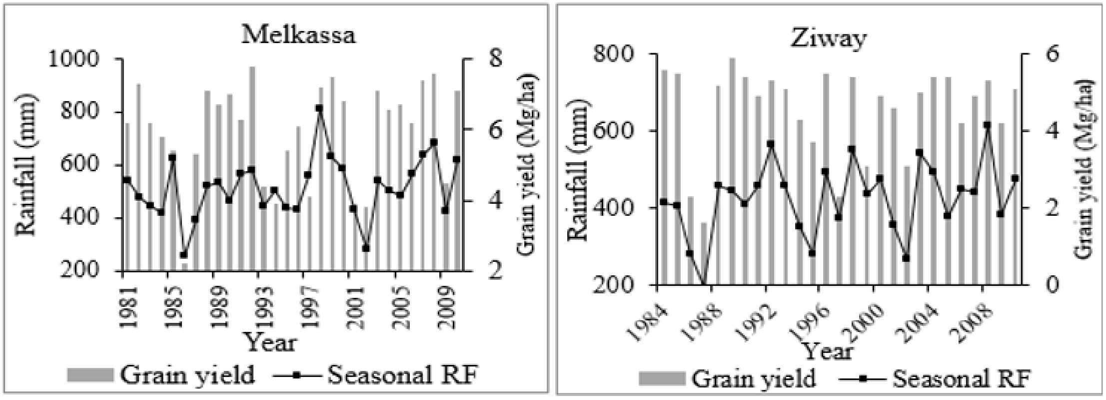
The analysis indicated that the amount of rainfall during the growing season explained about 44-48% of the variation in maize yield in the semi-arid CRV areas than other climatic factors considered. Rainfall can thus be considered as the most important variable which affects maize yield in these areas. Other studies ((Dixit et al., 2011; Müller et al., 2011; Kassie et al., 2014)) confirmed that climate-induced risks, and in particular rainfall-related risks, are the most important causes for uncertainty in crop production in most regions of the arid and semi-arid sub-Saharan Africa.

High dependence of yield to seasonal rainfall amount were clearly depicted at Melkassa and Ziway (Figure 3.3(a)). Higher seasonal rainfall (813 mm at Melkassa and 615 mm at Ziway) was received during the study period while the lowest (260 mm at Melkassa and 192 mm at Ziway) was observed. At both locations, higher yield was obtained in seasons with higher total seasonal rainfall whereas the lowest yield at both locations was associated with years with low seasonal rainfall. Several reports indicated that availability of soil water either from rainfall or irrigation is crucial in determining yield and yield related components. For instance, Earl and Davis (2003) indicated that water stress reduced yield, accumulated biomass, and harvest index of maize. Pandey et al. (2000) reported that when limited irrigation during the maize vegetative period was imposed, grain yield was reduced by 7% to 11% relative to the fully irrigated practice, and when water deficit occurred during the vegetative stage and early flowering stage, significant yield reductions of 23 to 26% were observed.

Water shortages and heat stress are two of the most important temperature effects limiting crop growth, development, and yield (Prasad & Staggenborg, 2008). Among the two, the significant negative relationship of temperature and yield at Ziway might not be related with heat stress effects. Looking at the temperature records of the Ziway site, it can be seen that the increase in temperature was not reasonably enough to impose physiological heat stress to reduce yields. Lizaso et al. (2018) indicated maize temperature requirements with base and optimum temperatures of 8 and 34 °C, respectively. The authors in their study indicated more than 42°C of day temperature caused heat stress in maize which by far is higher than the recorded temperature in our study area.

Interestingly, actual evapotranspiration (ET), which is a function of rainfall, temperature and soil water holding capacity, strongly and positively correlated with grain yield at both locations (Table 3.4). Threshold values of around 400 and 300 mm of ET at Melkassa and Ziway, respectively were identified below which yield of maize is constrained to below 2 Mg ha^{-1}. The highest seasonal ET (733 mm at Melkassa and 481 mm at Ziway) was estimated during the study period while the lowest seasonal ET values estimated at Melkassa and Ziway were 441 and 310 mm, respectively. Higher ET was calculated for Melkassa than Ziway where a relatively higher yield values were observed for the same.

a) Seasonal rainfall



b) Evapotranspiration

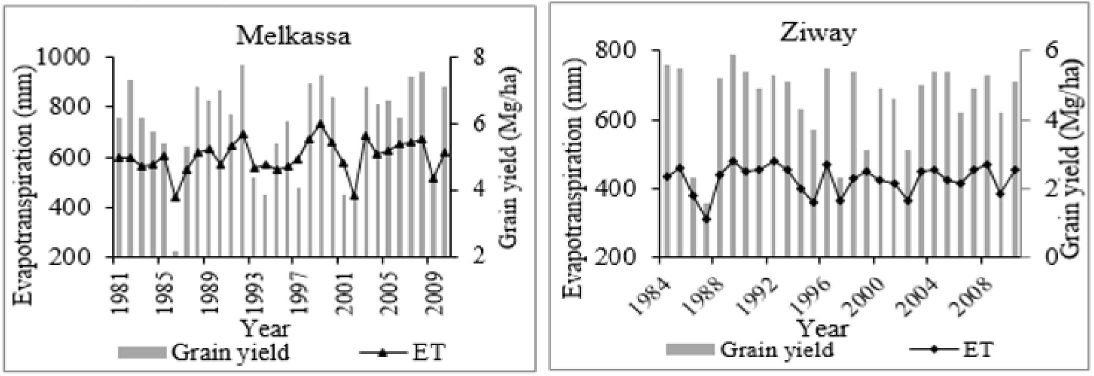


Figure 3.3. Relationship of simulated water-limited yield versus growing season rainfall (a) and evapotranspiration (b).

In consent with findings of the current study, a linear relationship between yield and ET was reported by some researchers (Hillel and Guron, 1973; Ko and Piccinni, 2009; Payero et al., 2009; Djaman and Irmak, 2012; Djaman et al., 2013). Payero et al. (2009) reported linear increase in maize yield and water productivity with increasing ET and with the ratio of ET to ET*p* (ET*p* = ET with no water stress). Hillel and Guron (1973) for example indicated a threshold evapotranspiration of 250-300 mm below which production was negligible and above which production rose linearly with the amount of water applied. The effect of water stress on maize ET*a* had also been studied experimentally (Stewart and Nielsen, 1990; Howell et al., 1995; Howell, 2001; Ko and Piccinni, 2009; Djaman and Irmak, 2012). One can infer from the result that management options which could enhance ET*a* in the sites have a significant influence on maize yield which especially benefit the Ziway site (low seasonal ET*a*). Looking at the calculated water holding capacity of the soil from Table 4.1, there exist a slightly higher water holding capacity (WHC) of soils of Melkassa (182 mm/m) than Ziway (176 mm/m). This insignificant differences in WHC of the sites could prove that ET*a* variations could result from variations in other climatic factors such as maximum temperature and rainfall received.

The high accounted variation in yield by seasonal evapotranspiration at both sites is also a good indicator that increasing plant available water through application of relevant soil moisture retention techniques could have a potential to increase ET*a* (by increasing transpiration over evaporation) thereby increase grain yield in the study locations. It can be concluded that an optimum soil water condition, permitting the crop to transpire at a rate approaching the climatically induced potential and simultaneously preventing the occurrence of moisture deficits, can help to realize the full productivity of the crop.

3.3.3.2 Potential and water limited yield level in the CRV

The mean potential yield simulated at Melkassa and Ziway were 8 (± 0.8) and 6.9 (± 0.6) Mg ha^{-1}, respectively (Table 3.5). The minimum and maximum potential yield at Melkassa during the simulation period was 7 and 9.7 Mg ha^{-1}, respectively. Similarly, the minimum and maximum potential yield at Ziway was 5.2 and 7.4 Mg ha^{-1}, respectively which was far lower than the corresponding yield at Melkassa. The relative potential yield difference at the two sites might be attributed to the negative effect of temperature at Ziway site, which could be related with the strong negative correlation of yield and temperature at the site (Table 3.4).

The mean water limited yield and standard deviation for the same simulation period at Melkassa and Ziway were 6 (± 1.4) and 4.9 (± 1.1) Mg ha^{-1}, respectively (Table 3.5). The water limited yield on the other hand, indicated the maximum yield that can be harvested under the given seasonal rainfall condition and with no nutrient stress. The highest water limited yield simulated for Melkassa was 7.8 Mg ha^{-1} while the lowest was 2.2 Mg ha^{-1}. The mean potential yield (averaged over site) of medium maturing maize (7 Mg ha^{-1}, in the range 6.5 – 8.6 Mg ha^{-1}) simulated by this study considerably agrees with previous studies made by Kassie et al. (2014) who simulated mean potential yield levels of early (6.8 Mg ha^{-1}) and late (8.2 Mg ha^{-1}) maturing cultivars of maize under the CRV conditions. Additionally, the result also is in good agreement with the highest yield of the cultivar reported from field experiments in the study areas. For instance, Bogale et al. (2011) indicated the potential yield of maize cultivar Melkassa-2 grown under no water stress condition is about 8 Mg ha^{-1}.

Table 3.5. Seasonal variations in climate variables and potential/water limited maize grain yield during 1981-2010, n = 30 for Melkassa and 1984-2010, n=27 for Ziway)

Variables	Melkassa					Ziway				
	Mean	SD	CV	Min	Max	Mean	SD	CV	Min	Max
Rainfall (mm)	514	114	22	287	821	423	97	23	192	615
Maximum temperature (°C)	27.3	0.6	2.2	26.3	28.7	24.6	0.5	2	23.8	25.6
Minimum temperature (°C)	14.4	1.1	7.3	10.1	15.7	14.2	0.4	3.1	13.4	14.9
Potential yield (Mg ha^{-1}) (a)	8	0.8	6.8	7	9.7	6.9	0.6	10.5	5.2	7.4
Water limited yield (Mg ha^{-1}) (b)	6	1.4	23.6	2.2	7.8	5.6	1.2	25.2	1.6	5.9
Yield gap due to irrigation (a-b)	2	1.4	68.2	0.4	5.7	1.3	1.3	101	0	5

SD: Standard deviation, CV: coefficient of variation (%), Min: Minimum value, Max: Maximum value

Since De wit (1958) developed the direct relationship between yield and transpiration, several researchers have proved the importance of increased amount of water application for higher yields (Hanks, 1974; Eck, 1986; Bakelana et al., 1986; Calvin et al., 2003; Yin et al., 2014; Mi et al., 2018). For example Eck (1986) indicated yields of maize were reduced by 1.2% for each day stress was imposed before normal maturity which eventually reduced yield of corn by 46%. Similarly, Calvin et al. (2003) indicated a non-linear increase in maize grain yield due to increased water application at flowering stage.

The same authors reported that more than 84% of variation in yield was accounted from variation in amount of water application. The multi role of water for plant growth and development and its physiological effects play a major role in affecting grain yield. For instance, Eck (1986) have shown that water deficit caused drastic reduction in net photosynthesis during grain filling. Other reports indicated that soil moisture level highly influenced yield through its effect on nutrient availability and transport there by influencing uptake of essential nutrients (Brouder and Volenec, 2008; Yin et al., 2014).

3.3.3.3 Yield level and variability under different nutrient conditions

The result revealed that mean grain yield was increased, on average by 15.1%, in the unlimited supply of nutrients than when conventional rate was used (data not shown). The simulated yield difference between the conventional fertilization rate and unlimited application of nutrients was higher at Melkassa 0.9 (±0.8) Mg ha^{-1} than at Ziway (0.75 (±0.8) Mg ha^{-1}) during the simulation period. The yield variability was higher for unlimited nutrient simulation at Melkassa (CV=23.5%) than the corresponding nutrient limited simulation (CV=16%) in the base period. Unlike Melkassa, yield variabilities did not show much differences at Ziway between nutrient limited (CV=25.3%) and unlimited simulations (CV=24.1%).

During the seasons of high rainfall, the crop responded to the increasing levels of available nutrients, whereas there was no difference in response to the applied nutrients during low rainfall conditions (Figure 3.4). The study might indicate, under conditions of inadequate water supply, applying high rates of fertilizer could even be damaging to the crop due to the osmotic effect it creates; unless there is balanced supply of production resources, it is almost impossible to get the desired/expected benefits. Our government's policy can be criticized in this regard that application of chemical fertilizers alone, they believe, can increase production and productivity. The results showed the importance of considering climatic characteristics of an area, in addition to soil characteristics, to draw sound fertilizer recommendations.

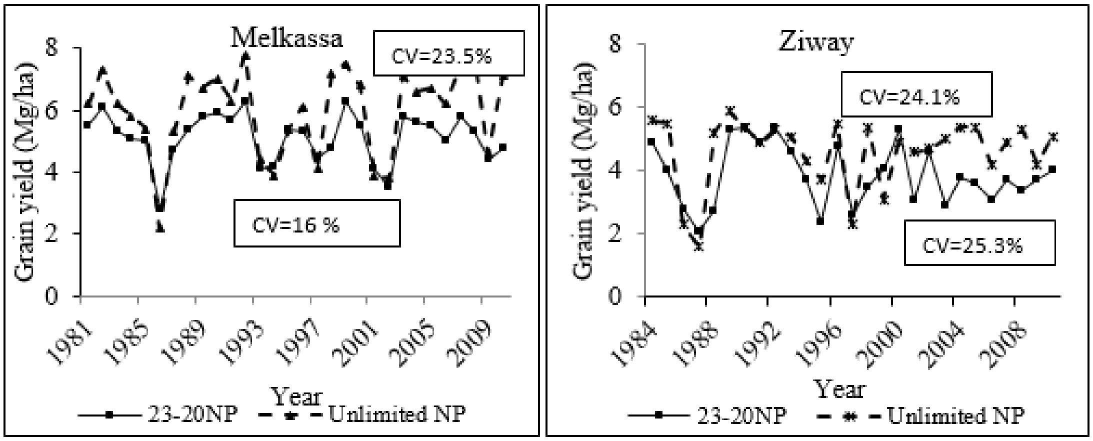


Figure 3.4. Yield variabilities and gap under conventional and unlimited nutrient supply.

The current findings are consistent with other similar results reported for the Central Rift Valley regions of Ethiopia. For instance, reports by Kassie et al. (2014) indicated that water limited maize yield variability ranged, on average, from 17 to 23% annually, which agrees with our current estimate. The strong dependence of maize yield on the amount of seasonal rainfall at Melkassa (r=0.669) and Ziway (r=0.69) was visible, and hence the high variation in rainfall at Melkassa (CV=22%) and Ziway (CV=23%) might have caused the variations in grain yield under optimum application of nutrients. Some studies indicated high inter seasonal variability of rainfall in the CRV of Ethiopia (Kassie et al., 2013; Bekele et al., 2016; Ademe et al., 2019). Similarly, studies indicated that the amount and temporal distribution of rainfall is generally variable and is the most important determinant of inter-annual fluctuations in crop production in Ethiopia with significant effects on the country's economy and food production (World Bank, 2006; Bewket and Conway, 2007; Hellmuth et al., 2007; Araya and Stroosnijder, 2011; Conway and Schipper, 2011; Demeke et al., 2011; Kassie et al., 2013; Kassie et al., 2014).

3.3.3.4 Yield gap analysis

Results of yield gap analysis indicated that actual maize yield obtained from farmers' field was far below yield obtained from research field, simulated for water limited yield and potential yield levels (Figure 3.5). The analysis revealed that the average maize yield from farmers' fields during 2007-2015 in the study areas under application of 23-20 kg NP ha^{-1} was 3.05 Mg ha^{-1}, which was lower than the corresponding yield obtained from researcher managed plots (4.97 Mg/ha at Melkassa and 3.69 Mg/ha at Ziway). The researcher managed yield excelled the farmers' yield by 21 to 63% in the areas which might be due to improved soil and crop management in the researcher managed fields. Furthermore, the yield from farmers field was 52 and 43% of the simulated water limited and potential yields respectively, indicating the existence of high yield gap in the region. Such huge yield gap of around 43% from what the environment could potentially offer imply that, use of proper inputs (irrigation, optimum fertilizer and plant protection) could dramatically improve yield by more than double in areas where irrigation resources are available. Moreover, in areas where rainfed farming is dominant, managing fertilizer and crop health alone could improve production of maize two folds and can ensure food security in the country.

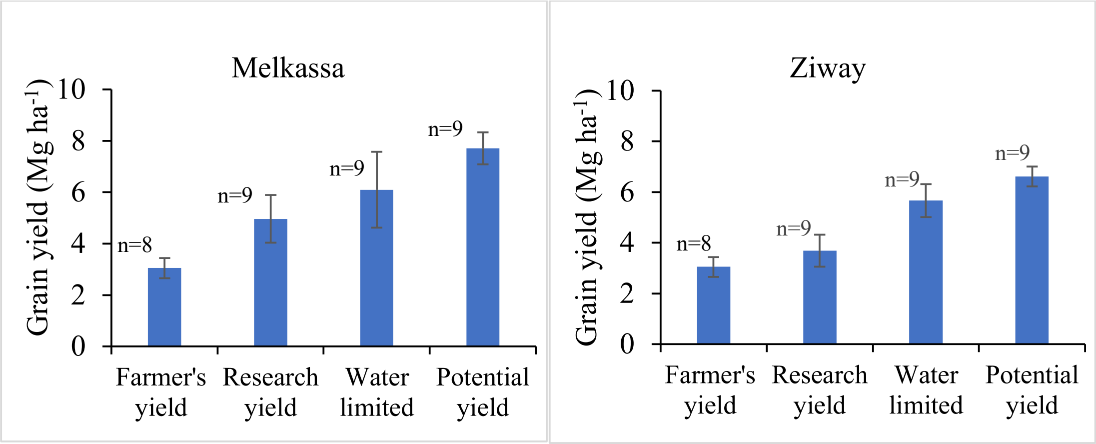


Figure 3.5. Yield gap of maize in the CRV of Ethiopia during 2007-2015 season.

The result agrees with the results of previous works conducted in the CRV conditions as well as similar agroecology in the Sub-Saharan Africa. For instance, Kassie et al. (2014) reported actual farmers' yields were 28–30% of simulated water-limited yield and 44–65% of researcher managed yields (on-farm trial) in the CRV of Ethiopia. The average yield gap of maize (6.5 t ha^{-1}) between farmers' and water limited yield was reported during 2004-2009 in the central lowlands of the Rift Valley (Getnet et al., 2016). Tittonell et al. (2008) also reported that the average farmers' yield of maize in Kenya was 25% of the water-limited yield potential indicating high yield gap in the area. Rötter (1993) and Rötter and Dreiser (1994) cited in (Kassie et al., 2014) found maize yields at moderate levels of N and P fertilizer application (e.g. 50 kg N/ha and 22 kg P/ha) reaching 40–60% of water-limited yields in semi-arid to sub-humid climatic zones of the Kenyan Rift Valley. Such yield gaps are very significant and much larger than in high-input agricultural systems (Kassie et al., 2014). The accuracy of yield gap estimates depends on appropriate estimates of water limited and actual yields in time (Van Ittersum et al., 2013).

The average fertilizer rate used by Ethiopian farmers is about 21 kg N/ha (Spielman et al., 2011), which is by far lower than the national recommendation rates of 60–100 kg N ha^{-1} (Debelle et al., 2001). Getnet et al. (2016) also confirmed insufficient application of fertilizers by farmers in the CRV of Ethiopia. The authors indicated the actual nitrogen (N) and phosphorus (P) application on farmers' fields was low (2.6–16.5 kg N ha^{-1} and 2.2–17.3 kg P ha^{-1}), whereby the best performing farmers, on average, apply 8–20 kg N ha^{-1} and 5–21 kg P ha^{-1} in the CRV maize growing areas. The soil nutrient balances are thus in many cases negative (Abegaz and van Keulen, 2009). Proper field management with supply of required inputs (fertilizer and improved seed) and increasing resource use efficiency through agro-advisory services, could increase crop yield and consequently narrow yield gaps (Kassie et al., 2014). However, increasing N application to recommended rates alone had only a small effect on narrowing the yield gap under current farmers' management (Getnet et al., 2016).

The long-term simulation was also done to see the difference in potential and water limited yield simulations, which indicated the yield gaps due to seasonal rainfall variations. The average yield gap at Melkassa (2 (±1.4) Mg ha^{-1}) was higher than that of Ziway (1.3 (±1.3) Mg ha^{-1}) for the prescribed simulation periods (Figure 3.6). Consequently, the yield gap varied from 0.4 to 5.9 Mg ha^{-1} at Melkassa and from 0 to 5 Mg ha^{-1} at Ziway for corresponding high and low rainfall years, respectively. It can be generalized that application of irrigation water could significantly improve production in these areas, especially during periods of high rainfall deficit. The high coefficient of variation in yield gap foretells seasonality in needs for irrigation water requirements at both locations. Given the wide yield gap especially during lower rainfall years across the simulation periods signify the requirement of more dependable application of irrigation water and potential shift to irrigated agriculture.

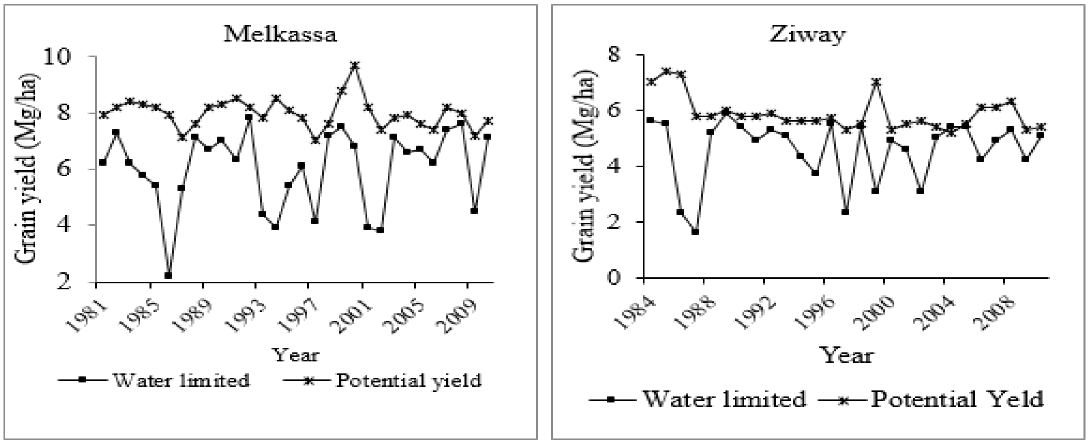


Figure 3.6. Potential and water limited yield variabilities and gaps in the CRV.

3.4 Conclusions

Sustained productivity under rain-fed conditions in dry areas is based on exploiting the synergy between soil and water conservation practices and supply of nutrients through mineral and organic sources. The study showed that maize production at Melkassa and Ziway is dependent on climatic factors (especially rainfall and temperature) and balanced application of nutrients. Maize productivity, nutrient uptake and use efficiency were higher during high rainfall years than low rainfall years. Additionally, increasing rates of nutrient application also improved productivity of maize, water productivity and nutrient use efficiency during high rainfall periods. The yield gaps between farmers' fields and researcher managed plots were mainly attributed to application of optimum rates of nutrients indicating that the conventional blanket recommendation of N and P used by farmers is not sufficient. Thus, site-specific fertilizer recommendations and strategies such as 'response farming' should be developed to improve productivity of the crop, its water and nutrient use efficiencies, and to reduce the yield gaps between farmers' fields and potentially attainable yields. Furthermore, use of irrigation, where irrigation water is available, is recommended for improved production and resource use efficiency in the CRV of Ethiopia. However, long-term field experiments for nutrient use efficiencies is required to draw sound conclusions.

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CHAPTER FOUR

Assessing Impacts of Climate Change on Water Productivity and Nutrient Use Efficiency of Maize in the Central Rift Valley (CRV) of Ethiopia

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4 Assessing Impacts of Climate Variability and Change on Water Productivity and Nutrient Use Efficiency of Maize in the Semi-arid Central Rift Valley of Ethiopia

Abstract

Changes in precipitation, temperature and atmospheric CO_2 concentration, are expected to alter agricultural productivity patterns worldwide. The interactive effects of soil moisture and nutrient availability are the two key edaphic factors that determine crop yield and sensitive to climatic changes. The study assessed the potential impacts of climate change on maize yield and corresponding water productivity and nutrient use efficiency under climate change scenarios for the Central Rift Valley of Ethiopia by mid (2041-2070) and end century (2071-2100). Projected impacts were evaluated using climate scenarios generated from four General Circulation Models (GCMs) dynamically downscaled by the Swedish RCA4 Regional Climate Model (RCM) in combination with two Representative Concentration Pathways (RCP 4.5 and RCP8.5). Decision Support System for *Agro-technology Transfer cropping system model (DSSAT-CSM) was used to simulate yield, water and nutrient use for the study periods. Results indicate that rainfed maize yield might decrease on average by 16.5 and 23% by 2050s and 2080s, respectively due to climate change. The water productivity is expected to decline on average by 2.2 and 12% in the CRV by mid and end centuries with respect to the baseline. Nutrient uptake and corresponding nutrient use efficiency (NUE) might also be negatively affected by climate change. Phosphorus uptake probably will decrease in the CRV on average by 14.5 to 18% by 2050s while N uptake may not change significantly at Melkassa. Nitrogen and P use efficiency indicators showed decreases in the range between 8.5 to 10.5% and between 9.3 to 10.5%, respectively by 2050s relative to the baseline average. The simulation results further indicated that combination of increased water availability and optimum nutrient application might increase both water productivity and nutrient use efficiency in the changed climate which can ensure modest production in the future. Potential options that can improve water availability and nutrient uptake should be identified for the study locations using crop modeling approach.*

Key: Regional climate model, Nutrient uptake, climate scenario, Crop model

4.1 Introduction

Climate change variables including precipitation (amount and distribution), temperature and atmospheric CO_2 concentration are expected to alter agricultural productivity patterns worldwide. Higher global temperatures and altered precipitation patterns are expected to accompany the higher CO_2 levels, and these factors may lessen or negate any production increases or even depress production below current levels (Brouder and Volenec, 2008). Consistent to global studies, climate change and its associated variability is expected to negatively affect agriculture in most parts of Africa especially the semi-arid areas in Sub-Saharan countries (Hellmuth et al., 2007; Thornton et al., 2011).

Nevertheless, with any potential changes in agricultural productivity comes a potential for associated changes in crop water and nutrient uses. Local potential yield levels are majorly determined by prevailing climate, ambient CO_2 and crop characteristics, but these yields are almost always limited by root zone resources such as nutrients and water (Brouder and Volenec, 2008). The interactive effects of soil moisture and nutrient availability are the two key edaphic factors that determine crop yield (Ziska and Bunce, 2007) and are directly or indirectly affected by climatic changes. Current nutrient management recommendations of a country are based on an understanding of crop-specific needs for achieving expected yields and soil-specific nutrient supply characteristics but the story will definitely be different under changed climate.

Nutrient use efficiency (NUE) and water productivity (WP) are critically important concepts in the evaluation and sustainability of crop production systems. Nutrient use efficiency can be greatly impacted by fertilizer management as well as availability of soil water in the root zone. Water productivity on the other hand can be majorly affected by alterations of potential evapotranspiration of the area as well as soil water management. Increasing water productivity is particularly appropriate where water is scarce and one needs to realize the full benefits of other production inputs, such as fertilizers. In addition, crops with high water requirements cultivated under semi-arid or arid conditions require to be adapted to the new climate conditions to increase water productivity and irrigation water efficiency (Molden et al., 2010) in an elevated temperature environment (Lizaso et al., 2018). Better understanding, measurement and improvement of water productivity and nutrient use efficiency of a given agricultural system would thus constitute a strategic response to growing water scarcity and nutrient loss (Drechsel et al., 2015) especially under changing climate.

Given that cereal production is predominantly rain-fed, variability and unpredictability of rainfall and increments in temperature has always been a major concern in Ethiopia (Kassie et al., 2015). It is also evident that, among the diverse agroclimatic zones of the country, the arid and the semi-arid areas which receive the lowest and most erratic rainfall are severely affected by the changing climate. The Central Rift Valley (CRV) is one of those regions which experience frequent natural hazards such as recurrent droughts and chronic water stress. The predominant livelihood strategy for the majority of the population (about 2 million) in the CRV is the small mixed rain fed farming system comprising cereals (wheat, barley, maize and teff) and livestock (Meshesha et al., 2012; Getnet et al., 2014) which is prone to climatic shocks. Although the cropping system of the CRV where the study was implemented is predominantly maize based, scientific evidences suggest that higher temperatures and changing precipitation levels as a result of the changing climate will have a negative effect in terms of maize yield over the coming decades (Kassie et al., 2015). The main reason for focusing in the CRV is thus not only due to its vulnerability to climate change but also its being major maize growing belt where attempts have been made to reduce nutrient constraints to maximize production and ensure food security to feed the ever-growing population.

Few studies have been conducted to show the effect of climate on soil which is a major reservoir and supplier of macro and micro nutrient to all kinds of crops grown on it. Karmakar et al. (2016) for example reviewed that climate change affects the physical, chemical and biological properties of soil which have a direct and indirect effect on the availability and dynamics of plant nutrients. Studies on global climate change and mineral nutrition remain relatively sparse, with nitrogen being the primary focus of previous research (Brouder and Volenec, 2008). In sum, climate will change but details regarding impact on agriculture remain vague. Mineral stressors on crop production are one of the many biotic and abiotic uncertainties that contribute to our inability to predict future food supply. Lynch and St Clair (2004) identified this as a critical gap in climate change studies, noting that most plant systems, natural and agricultural, having suboptimal nutrient availability and mineral stress interactions with global climate change variables are likely to be important but remain understudied.

To date, few studies has been conducted to understand the influences of climate variability and change on yield of few crops (Kassie et al., 2013a; Kassie et al., 2014; Kassie et al., 2015; Getnet et al., 2016) and resources use efficiencies under current climate (Getnet et al., 2016) in the study area. Since resource use efficiencies are highly variable as a result of soil variability and climate conditions (Tittonell et al., 2008), the projected changes in climate of the CRV of Ethiopia might greatly affect the agricultural efficiency in terms of resources use and total agricultural production. However, the studies conducted so far did not present the efficiencies of the agricultural system under different nutrient and water management scenarios in the changing climate conditions which will be critically important for adaptation planning. Limited availability of information on resources use efficiencies significantly hampers the identification of strategies for the development of improved agricultural systems which eventually affect millions of people vulnerable to climate shocks in the region.

To avail such evidences to inform policies and better planning of interventions and preparedness in the coming years, simulation modeling can be a powerful tool to estimate the impacts of climate variability and change on growth, yield and resource uses of crops given that data on soil and climate are available (Jones et al., 2003) and helps to identify interventions and inform stakeholders for adaptation efforts ahead of time (Kassie et al., 2013a; Kassie et al., 2015). Understanding the resource use and RUEs of the future production systems helps to shape policy decisions to identify possibilities of producing more with the available resources in the face of climate change. The objective of this study was thus to model how the changing climate likely affect water productivity and nutrient use efficiency (N&P) of maize in the drought prone maize growing areas of the CRV of Ethiopia.

4.2 Materials and Methods

4.2.1 Climate data source and climate models used

Daily weather data for the period 1981-2010 representing the present climate, hereafter referred to as baseline, of Melkassa and Ziway sites was obtained from the National Meteorological Agency of Ethiopia (http://www.ethiomet.gov.et). Data quality of the baseline period was priorily ensured and published by Ademe et al. (2020). Corresponding projected changes in rainfall and temperature for each station were analyzed based on eight combinations of four Global Climate Models (GCMs), one Regional Climate Model (RCM) and two Representative Concentration Pathways (RCPs). The climate models' description and downscaling procedures are portrayed under chapter two.

4.2.2 Climate change scenario and time frame used for the Study

The time horizon for the climate change scenario analysis was for the mid-century (2041-2070), and for the end century (2071-2100) hereafter referred to as mid and end century, respectively. The sensitivity of the climate system to an increase in greenhouse gas concentration was considered with low and high emission scenarios. The RCPs and their corresponding atmospheric CO_2 concentration are presented in detail by van Vuuren et al. (2011) as shown in Table 4.1.

Table 4.1. Representative concentration scenarios, their time coverage and CO_2 concentration used in this study

Scenario	Period (Coverage)	Mid-year	CO_2 concentration (ppm)
Baseline	1981-2010	1995	360
Mid_RCP4.5	2041-2070	2055	499
Mid_RCP8.5	2041-2070	2055	571
End_RCP4.5	2071-2100	2085	650
End_RCP8.5	2071-2100	2085	1370

4.2.3 Crop simulation model used

In this study, Decision Support Systems for Agro-technology Transfer (DSSAT-CSM, v4.7), hereafter referred to as DSSAT model was used to assess impacts of climate change scenarios on maize yield and corresponding resources use efficiency in the CRV of Ethiopia.

The DSSAT model was chosen because it is well accepted and widely used for analyzing the impacts of climate change and allow the incorporation of elevated levels of atmospheric CO_2 and evaluating various management options (White et al., 2011; Rötter et al., 2012; Kassie et al., 2015).

Details of the relevant modelling approaches of the DSSAT model is thoroughly presented in chapter 3. In addition, the model was previously calibrated and tested for Melkassa-2 maize cultivar in the CRV of Ethiopia and the details of model evaluation are presented under chapter 3. For the climate change impact analysis, the widely cultivated medium maturing (130 day) maize cultivar (ZM521) was used in this study.

To account for the effects of elevated CO_2 on crop growth and yield, simulations were carried out by keeping the CO_2 concentration at the current level for the baseline period and by changing the CO_2 concentrations for each climate change scenario to their corresponding level (e.g. (Alexandrov and Hoogenboom, 2000; Ruane et al., 2013; Kassie et al., 2015). The evapotranspiration routine in the DSSAT crop model includes the ratio of transpiration under elevated CO_2 concentrations to that under baseline concentration (Alexandrov and Hoogenboom, 2000). The key procedures of the simulation experiment were (i) running the crop models with the current (baseline) and climate change scenarios (ii) comparing these crop model results to quantify yield changes, changes in nutrient uptake and calculating resource use efficiency and (iii) analyzing the effects of the various management strategies (such as application of different levels of fertilizers and water) and selecting promising options which reduce negative impacts of climate change and improve resource use efficiency. The evaluation of climate change impact on yield and resource use efficiency covers, the different NP fertilization levels, water limited (rainfed) and non-water limited simulations (full irrigation) and combination of NP fertilization and irrigation options. Furthermore, climate change impact simulations assume that pests and diseases are controlled and that no problematic soil conditions such as salinity and acidity prevail. Similarly, soil depth remains similar with the baseline conditions and micronutrient level will be optimum throughout the simulation period. Moreover, there will not be occurrences of catastrophic weather events.

4.2.4 Crop management scenarios for climate change impact assessment

4.2.4.1 Determination of planting dates

Different approaches are documented to set planting dates in crop simulation studies (Kassie et al., 2015). A list of publications reported use of pre-defined sowing dates based on observations (e.g. Alexandrov and Hoogenboom, 2000; Jones and Thornton, 2003; Liu et al., 2008; Laux et al., 2010), while some others used optimization algorithms, which select sowing dates based on crop water and temperature requirements (e.g., Bondeau et al., 2007). Another approach is to optimize sowing dates by selecting the date which leads to the highest simulated crop yield (e.g. Žalud and Dubrovský, 2002; Soler et al., 2008; Waha et al., 2012). Following prior similar simulation studies in the CRV by Kassie et al. (2015), sowing dates for the baseline and climate change scenarios were determined based on the first occurrence of rainfall between April 15 and July 7 while fulfilling a requirement of at least 40 mm of rainfall accumulated within 4 rainy days. The same approach was also reported by Raes et al. (2004) for Zimbabwe; Kipkorir et al. (2007) and Mugalavai et al. (2008) for Kenya in Africa. It is assumed that the timing of sowing is dependent on rainfall onset, which is typical in (semi)-arid environments and is a common practice in the CRV (Kassie et al., 2013b; Ademe et al., 2019).

4.2.4.2 Nutrient management scenario

We simulated the impacts of climate change on maize productivity and resources use efficiency under various combinations of nitrogen and phosphorous fertilizers. The combinations include low, which represents the locally applied rate (23-20 kg NP/ha), medium (69-40 kg NP/ha), high (120-60 kg NP/ha) and very high fertilization (no nitrogen and phosphorus limitation), while other essential nutrients including K are assumed to be adequately supplied in all cases. The low nitrogen (20 kg/ha) is approximately the average application rate currently used for maize in Ethiopia (Spielman et al., 2011; Cairns et al., 2013; Getnet et al., 2016) and the high and very high NP fertilizer levels were considered, with a somewhat optimistic perspective, for climate change adaptations in the future period. The sources of N and P were assumed to be urea and DAP respectively, which are currently the most frequently applied fertilizer sources in Ethiopia. Band application of fertilizers was made near the root zone at 5 mm depth. Nitrogen application for low, moderate and high doses was split between 66% at planting and 34% at 30 days after planting, which is a common practice in the study area.

4.2.4.3 Water availability scenarios

Considering the prospects for irrigation, the study assessed its effects as an adaptation option under a range of climate change scenarios. The simulations for the different climate change scenarios were conducted under rainfed and full irrigation (no-water stress) with no nutrient limitation conditions as well as under different levels of nutrient application to gain insight into the possibilities of optimum management (full irrigation and full fertilization) and limitations for each input is pronounced in crop yields in the changed climate.

4.2.5 Determination of water productivity (WP)

The concept of water productivity (WP) was offered by Kijne et al. (2003) as a robust measure of the ability of agricultural systems to convert water into food. So, the basic expression of agricultural water productivity is a measure of output of a given system in relation to the water it consumes, and may be measured for the whole system or parts of it, defined in time and space (Cook et al., 2006). The study computed water productivity using the following relationship:

$$\mathrm{WP} = \frac{\mathrm{GY}}{\mathrm{AETc}} \tag{4.1}$$

WP = water productivity in kg[yield]/ha per mm [ET], GY = grain yield in kg[yield]/ha, and $\mathrm{AET_C}$= actual crop evapotranspiration in mm.

Water productivity is estimated from the amount of water directly consumed by the agricultural system (evaporation and transpiration) and not the amount of rainfall received (Molden et al., 2010). Hence, the model estimated the water used using the following water balance equation:

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} + \mathrm{G} + \mathrm{Q} - \Delta \mathrm{S} \tag{4.2}$$

where, ET is Evapotranspiration, P – precipitation (measured daily rainfall value), I – irrigation (measured daily irrigation amount), G - net groundwater flow (estimated by DSSAT model), Q - run-on or runoff (estimated by DSSAT model) and ΔS - change in soil water content within the root zone (estimated by DSSAT model), all measured in millimeters of water.

4.2.6 Determination of nutrient use efficiency

Nutrient use efficiency (NUE) is a critically important concept in the evaluation of crop production systems especially under changing climatic conditions. The study used the following equations to determine the efficiency of the nutrients under different nutrient levels as stated in Dobermann (2007).

Agronomic efficiency (AE), is a short-term indicator addressing how much improvement was gained in productivity by use of nutrient input.

$$AE = \frac{Y\text{-}Y_0}{F} \tag{4.3}$$

Apparent recovery efficiency (RE), is an indicator of the potential loss of nutrient from the cropping system and also assess the efficiency of management practices.

$$RE = \frac{U\text{-}U_0}{F} \tag{4.4}$$

Physiological efficiency (PE) measures the ability of the plant to transform nutrients acquired from the source applied into economic yield.

$$PE = \frac{(Y\text{-}Y_0)}{(U\text{-}U_0)} \tag{4.5}$$

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of “removal to use”).

$$PNB = \frac{U_H}{F} \tag{4.6}$$

Where: Y = yield of harvested portion of crop with nutrient applied (kg/ha); Y_0 = yield with no nutrient applied (kg/ha); F = amount of nutrient applied (kg/ha); U_H = nutrient content of harvested portion of the crop; U and U_0 are total nutrient uptake in above ground biomass with and without nutrient applied, respectively.

For the projected period, simulations were carried out with projected weather data for mid (2041 – 2070) and end century (2071 – 2100) to evaluate the response of N&P fertilizer and corresponding resources use efficiency indices and their interaction under RCP4.5 and RCP 8.5 climate change scenarios. Percent change in simulated yield, resource use efficiency and climate variables in the projected period from the baseline was calculated using the following equation

$$\% \Delta = \frac{\text{Proj - Baseline}}{\text{Baseline}} \text{ X } 100\% \tag{4.7}$$

where, Proj = projected value; Baseline = baseline value; Δ= change

4.2.7 Uncertainty assessment for climate impact projections

In this study, we consider the uncertainties of the selected CGCMs and RCPs in projecting climate change impacts in the future period. To assess the uncertainty due to the choice of CGCMs and RCPs, we determined the range of uncertainty exhibited by the individual CGCMs/RCPs for each climate change impact projections. Heo et al. (2014) defined the range of uncertainty for each station as a maximum minus minimum of the future projection obtained from the suite of the 4 CGCMs and for the 2 RCPs employed in this study for the mid and far period; then, the ratio of this range to multi-model ensemble mean (MMEM) change was calculated. Wider range of uncertainty among the selected models indicate higher uncertainties in the projection of future climate change impact estimates while narrow ranges indicates more certain estimates (Heo et al., 2014).

4.3 Results and Discussions

4.3.1 Baseline and projected changes in hydro-meteorological variables

4.3.1.1 Changes in temperature

Hydro-meteorological variables have shown changes in the projected period as compared to the baseline conditions in the semi-arid CRV of Ethiopia under ensemble average of climate models scenario (Table 4.2). The multi model ensemble projections indicated, under each RCP scenario temperature showed an increase for mid and end century projections in the study areas. Mean daily average temperature increases (averaged over RCPs) were simulated on average by +1.8 °C (1.5 °C– 2.1 °C) at Melkassa and +2 °C (1.6 °C – 2.3 °C) at Ziway in the mid period relative to the baseline period. Further warming of the main season was also projected by 2.8 °C (1.9 °C – 3.3 °C) and 3 °C (1.6 °C – 3.9 °C) at Melkassa and Ziway, respectively by the end century.

Table 4.2. Baseline and future period crop production-influencing factors in the CRV

Period_RCP	Melkassa					Ziway				
	T_{av}	RF	ET	RO	WP	T_{av}	RF	ET	RO	WP
Baseline	20.8	517	496	135	10	19.4	441	413	113	10.6
Mid_RCP4.5	22.3	473	459	114	8.6	21	396	388	95	10.6
Mid_RCP8.5	22.9	487	448	122	8.9	21.7	373	364	93	10.6
End_RCP4.5	22.7	519	483	120	9.2	21.4	397	376	94	10.7
End_RCP8.5	24.5	446	418	107	8.1	23.3	301	326	73	9.8

T_{av} = mean seasonal daily average temperature (ºC); RF= Seasonal total rainfall (mm); ET= Seasonal total evapotranspiration (mm); RO= Seasonal cumulative runoff (mm); WP = water productivity (kg [yield]/mm [ET]. Season = June to October

This result is consistent with previous studies and reports for Ethiopia. For example NMA (2007) reported that the annual temperature is expected to increase in the range of 2.7 to 3.4 °C by the 2080s compared to the 1961-1990 base period. Our previous spatial analysis of temperature across the GRVB also confirmed similar increases in temperature (see Chapter 3). The highest increases are indicated in the lowland areas (the study areas) which are currently characterized by extremely high temperatures (AvT > 19°C) in the basin. The climate change seems to worsen the situation in the currently hotter regions in the future. Similar results were also reported for global scale projections. The Fifth IPCC assessment synthesis report suggested an increasing trend of temperature in the range of 1.4 to 4.8ºC by the end of the century under RCP4.5 and RCP8.5 emission pathway (IPCC, 2014). Regional and sub regional warming was also indicated for East and Central Africa by about +2 ºC during 2050s (Kwena et al., 2018).

4.3.1.2 Changes in rainfall in the study sites

Seasonal rainfall, unlike temperature, showed irregularities in its periodic change at Melkassa than Ziway. However, it can be noted that at both locations, the future did show considerable declines in the total amount of rainfall received during the main season although it will be higher for RCP 8.5 climate change scenario in the far periods. Consequently, a decline in seasonal total rainfall by 7.2% at Melkassa and 12.8% at Ziway has been projected during mid-century. Similarly, in the far century, the decline in precipitation (-6.7% at Melkassa and -20.9% at Ziway) would continue in the CRV leaving the area drier than the baseline condition. Our result agrees with past research findings on future rainfall projections for Ethiopia (Arndt et al., 2011; Kassie et al., 2015). A decrease of main season rainfall by 4 to 20% for the Central Rift Valley was previously reported during the mid-period under RCP4.5 and RCP8.5 emission scenario with respect to the baseline period (Kassie et al., 2015). Similar result was also reported by Arndt et al. (2011) indicating that the main season rainfall might decline by 20% in the far period relative to the 1960-1990 period.

4.3.1.3 Changes in evapotranspiration

Increases in temperature and corresponding declines in seasonal rainfall might likely affect actual evapotranspiration, water productivity and runoff negatively at both RCPs and periods. Decline in actual evapotranspiration (averaged over RCPs and Sites) in the mid-century by 8.8% and far century by 12.1% was projected in the CRV maize growing areas. The study also highlighted that, runoff might likely decline on average by 14.7% in the mid-century and the decline might further escalate up to 21% by the end of the century with respect to the baseline condition. The changes in ET and runoff seems associated with the relative changes in seasonal total rainfall received in the study areas. Projected declines in rainfall and corresponding increases in temperature likely reduced ET on both periods as compared to the baseline conditions. It seems that rainfall changes by 7.2% likely reduced ET by 8.6% for Melkassa in mid period and was found similar for the far period.

In agreement with this study, different studies showed proportional increases of ET by 33.2 and 13% has been reported for a corresponding increases in seasonal rainfall by 27 and 12.1% in the US Cornbelt and southern plain regions, respectively during the far period (Brouder and Volenec, 2008). The influence of changes in seasonal rainfall (water stress) on ET was also reported by several researchers (Howell, 2001; Brouder and Volenec, 2008; Ko and Piccinni, 2009; Djaman and Irmak, 2012). Similarly, runoff showed the same pattern of relationship with the seasonal rainfall received. An insignificant decrease in runoff was projected in the US southern plain region where the percent increase in rainfall is relatively small while runoff significantly increased for regions with projected high increases in rainfall (Brouder and Volenec, 2008). In places where rainfalls decline, there will be much larger corresponding reductions in surface runoff (Milly et al., 2005). It can also be noted that increases in temperature have a stronger effect to changes in ET and runoff when the change in seasonal rainfall is small. In all cases where rainfall, runoff and groundwater recharge decline, current tensions between agricultural and environmental allocation of water will be magnified (Turral et al., 2011). The declining trend of ET and runoff however signals potential reduction in crop yield and runoff-water that can potentially be harvested in the future, respectively.

4.3.2 Impact of climate change on maize production in the CRV of Ethiopia

Increases in air temperature and changes in precipitation will significantly impact prevailing root zone temperature and moisture regimes. Under ensemble average climate scenarios, the projected changes in mean grain yield of maize in the mid and far period is summarized for Melkassa and Ziway (Table 4.3). Grain yield under water limited (rainfed) conditions was projected to change by -15 to -18.3% at Melkassa and by -6.5 to -10.5% at Ziway in the mid-century with respect to the base period. Similarly, the decline becomes worse for both locations during the end of century where the yield decline might escalate in the range of -21.1 to -25.3% in the worst-case scenario (RCP8.5). Although, the simulated changes in grain yield were very alarming for both RCPs and periods, the expected loss in yield at Melkassa (-15 to -23.3% in the mid and -8.4% to -32.5% in far periods) was found to be higher than the losses expected at Ziway (-5.3% to -13.2% in the mid and from 0 to -31.6% in the far periods). The future climatic scenario holds great challenges on rainfed crop production that in-turn could significantly impact food security of the region.

Table 4.3. Changes in grain yield (GY) (Mg/ha) of maize under water limited (WLY) and potential (PY) simulation for mid and far period with respect to the base period

Period_RCP	Melkassa (n =30)				Ziway (n = 27)			
	GY (WLY)	% Δ	GY (PY)	% Δ	GY (WLY)	% Δ	GY (PY)	% Δ
Base Period	6.0		8.0		5.9		6.9	
Mid_RCP4.5	4.9	-18.3	6.1	-23.8	4.3	-6.5	5.4	-21.7
Mid_RCP8.5	5.1	-15	5.9	-26.7	4.1	-10.5	5.1	-26.1
End_RCP4.5	5.2	-12.7	6.0	-25.3	4.3	-5.9	5.2	-24.6
End_RCP8.5	4.5	-25.1	5.3	-33.2	3.6	-21.9	4.5	-34.8

The potential yield (under no water and nutrient limitation) of maize also showed a significant decline ranging from 23.8 to 26.7% at Melkassa and from 21.7 to 26.1% at Ziway by mid-century under RCP4.5 and RCP8.5 climate change scenarios, respectively. Further increases in temperature in the end century increased yield losses in the range of -25.3 to -33.2% at Melkassa and from -24.6 to -34.8% at Ziway under RCP4.5 and RCP8.5 climate change scenario, respectively. Projected maize yield reduction under no water and nutrient stress conditions could imply the existence of other equally important factors such as temperature and CO_2 concentrations that can potentially limit crop production.

Under potential yield simulation the most possible growth factors which are changed over time include temperature and CO_2 levels. Most studies reported that increases in CO_2 concentration in the atmosphere has shown a beneficial effect to grain yield than the reverse (Guo et al., 2010; Kassie et al., 2015). However, the effect of heat stress due to increased temperature have been reported to reduce grain yield (Cicchino et al., 2010; Gourdji et al., 2013; Lizaso et al., 2018) which might be the major cause to simulated yield reduction in the region. The study result necessitates development of heat tolerant varieties through breeding programs to ensure food security in the warming future scenarios which the current varieties could not suffice and adapt to the changed conditions.

Although yields under irrigation showed projected declines in the changing climate as compared to the baseline, irrigation will still remain a viable option to increase production in the changing climate. For the current variety of maize irrigation treatments excelled rainfed treatments in all the considered RCPs and periods. The result indicated a 24.5 and 15.7% yield increases of using irrigation over rainfed in the mid period under RCP4.5 and RCP8.5 scenario, respectively. Similarly, 15.4 and 17.8% yield advantage were simulated for irrigated maize than the rainfed under RCP4.5 and RCP8.5 scenario, respectively in the far period. Currently staple crops are commonly produced under rainfed conditions in the study area. However, irrigated vegetable production is rapidly increasing near suitable ground water and surface water resources in the area (Van Halsema et al., 2011), and points at possibilities for irrigated staple production as well (Kassie et al., 2015). In addition, water harvesting through capture of runoff in reservoirs that can be used to irrigate crops when rainfall is insufficient to secure crop harvest is strongly promoted by the Ethiopian Government and various foreign donors (Moges et al., 2011). Expansion of small-scale irrigation is among the top priorities of stakeholders in the CRV (Kassie et al., 2013a) and has been identified as a promising adaptation strategy in NAPA (NMA, 2007) which is in favor of the present findings.

The individual model simulation results of changes in yield and climate variables are portrayed for the study sites in Appendix Table 8 for Melkassa and Appendix Table 9 for Ziway under water limited condition for mid and end century. The result showed that, in the mid-century, all climate models projected declines in grain yield ranging from -11.7% by ECEARTH-RCP8.5 to -23.3%, HadGEM2-ES-RCP4.5 at Melkassa while the decline at Ziway ranges from -5.3%, ECEARTH-RCP8.5 to -13.2%, MPI-ESM-RCP8.5. The end century projections for the semi-arid CRV showed considerable losses in maize grain yield ranging from -7% by CNRM-RCP4.5 to -32.1% by HadGEM2-ES-RCP8.5 (averaged over sites). The overall mean decline in maize yield of the climate change scenarios and crop models was in agreement with previous studies by Kassie et al. (2015) who estimated 20% loss of early maturing maize yield by 2050s relative to the baseline in the CRV of Ethiopia. The result could imply that, in the future crop production might significantly be affected by climate change looming millions of people in the region to remain food insecure unless sound measures and preparedness took in place.

Globally, several researchers reported wide range of potential impacts of climate change on maize yield (Brown and Rosenberg, 1999; Reilly and Schimmelpfennig, 1999; Jones and

Thornton, 2009; Thornton et al., 2010; Schlenker and Lobell, 2010). Brown and Rosenberg (1999) for example found only small increases in yield with a temperature increase of 2.5 °C and large decreases in yield with a temperature increase of 5 °C in the US corn growing areas. Reilly and Schimmelpfennig (1999) estimated that maize yields in Africa may change between −98 and +16 % due to the impacts of climate change and elevated CO_2 concentration. Thornton et al. (2010) estimated a decline in maize yield for the region in the range of −25 to −6%. Another very consistent result with our findings were reported by Jones and Thornton (2009) and Schlenker and Lobell (2010) indicated maize yield reductions of about 22 % in sub-Saharan Africa by 2050s.

The projected declines in grain yield under water limited simulations might arise majorly from the projected declines in seasonal rainfall coupled with increased temperature that resulted in increased evaporation and decreased LGP. Water shortages and heat stress are two of the most important environmental factors limiting crop growth, development, and yield (Harrison et al., 2011). The effect of temperature in reducing the length of the growth cycle, especially the grain filling phase, is the most important factor in explaining reduced yields at warmer temperatures (White and Reynolds, 2003). Our earlier works clearly depicted that the semi-arid lowlands of the CRV showed significant declines in seasonal precipitation and elevated temperature leading to corresponding decrease in the length of growing season, increasing risks of in-season dry spell (frequency and spell length) and reduced water availability to satisfy crop water demand that can potentially harm crop yields (see chapter two for details).

In similar token, several researchers also identified heat stress as a main threat for future maize cultivation in several relevant production regions (Cicchino et al., 2010; Gourdji et al., 2013; Lizaso et al., 2018) even under unlimited water supply condition. Cicchino et al. (2010) for example showed that heat stress during the period around silking leads to high yield reduction. Heat stress affect yield by reducing carbohydrate synthesis (Barnabás et al., 2008), decreasing photosynthesis and escalating respiration rates (Rattalino-Edreira and Otegui, 2012; Ordóñez et al., 2015). Similarly, high temperature proved to reduce ovule fertilization and increased kernel abortion resulting in severe yield losses; (Cicchino et al., 2010; Rattalino-Edreira et al., 2011; Ordóñez et al., 2015).

The uncertainties exhibited by the climate models (-10% to -16.8%) in projecting yield in the CRV were higher than the two RCPs (-12.9% to -13.2%) in the mid period. Moreover, the uncertainty increased in magnitude in both climate models and RCPs alike in the end century. Consequently, in the mentioned period uncertainties in maize grain yield projections were slightly higher for the two RCPs (-9.9% to -25.6%) than the climate models (-12.2% to -24.4%) used for the study. Looking at the uncertainty level at both periods, one can be certain that yield reduction is eminent in the mid period that there could be a loss in the range of -10% to -16.8% under any of the representative concentration pathways. However, it should be noted that the analysis we have undertaken only used smaller number of climate models to conclude with considerable level of confidence.

The majority of the reports agree with the trend of our findings in that the future might be challenging to feed the ever-growing population especially in the semi-arid drought prone lowlands. In response to projected declines in maize yield, researchers recommended possible solutions including increasing nutrient fertilization, use of irrigation and changes in planting dates (i.e slightly shifting to late planting by three weeks relative to the baseline planting dates) to compensate the negative impacts of climate change on maize production in the CRV (Kassie et al., 2015). They also noted that, the response of yield to increased fertilization and irrigation supply will be less for climate change scenarios than the baseline climate implying that negative impacts of climate change will not be totally compensated due to increased temperature. Hence, developing high yielding and heat tolerant cultivars, and preferably also disease and pest-resistant, in order to effectively adapt crop production to future climate.

4.3.3 Trends of resources use efficiency of maize in the CRV

4.3.3.1 Baseline water productivity of maize under different nutrient levels

Following variations in seasonal rainfall amount at the study sites, WP showed non-significant trends regardless of levels of fertilizer application (Figure 4.1). During the 30 years period, WP at Melkassa showed 0.52 kg ha^{-1} mm^{-1} reduction by 2010 as compared to 1981 despite a 3.57 mm yr^{-1} (~107.1 mm per 30 years) increase in precipitation. Comparing the WP trends of optimum fertilizer application and recommended rate, it could be inferred that the decline in WP can be offset by improving the fertility status of the soil to an optimum level in the variable climate conditions of the study area. Although rainfall is an important variable affecting WP, monitoring other climate variables such as temperature would be equally important to improve water productivity under sufficient nutrient conditions. In general, a declining WP trend was observed in the CRV signaling the importance of increasing water productivity through various means in the study area.

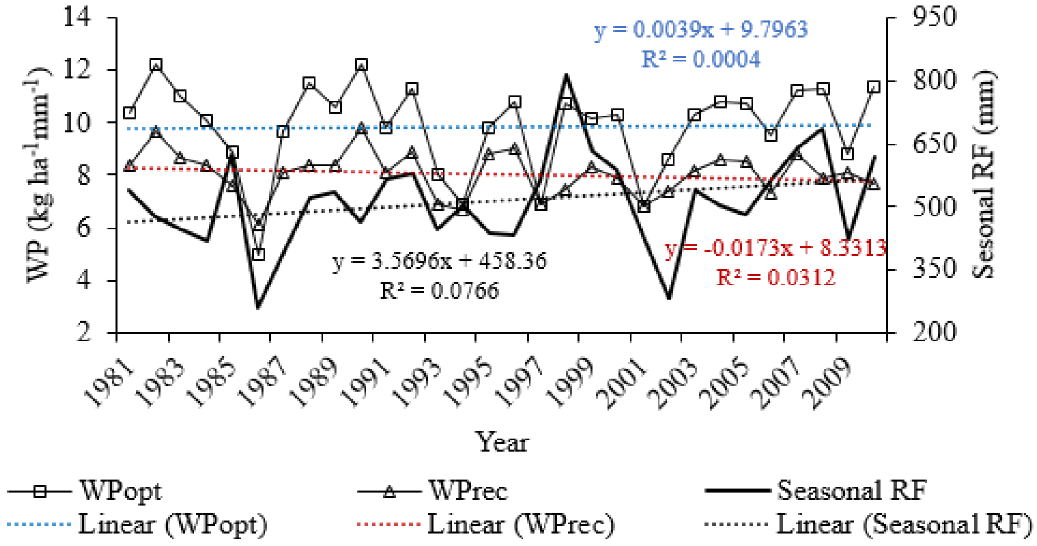

Figure 4.1. Water productivity trends of rainfed maize under optimum (WPopt) and recommended (69-20NP) (WPrec) fertilizer rates at Melkassa, CRV of Ethiopia.

The combined effects of levels of nutrient applications and seasonal rainfall amount is crucial to devise option for improving WP. Under optimum nutrient condition for example, the lowest WP (5 kg ha^{-1} mm^{-1}) was simulated during the year with low seasonal rainfall (260 mm) while the highest WP (10-12.2 kg ha^{-1}mm^{-1}) was recorded in the highest rainfall years (> 500 mm). Similarly, under recommended fertilizer rate, the lowest WP (6.1 kg ha^{-1} mm^{-1}) was obtained during low rainfall year while the highest WP (9.8 kg ha^{-1}mm^{-1}) was simulated in the high rainfall years. The result revealed that during years of low seasonal rainfall, application of unlimited fertilizer amount did not bring about rainwater productivity improvement. However, in years with considerably high seasonal rainfall, application of optimum fertilizer significantly improved WP in the CRV of Ethiopia.

The study also indicated that the interaction effects of moisture and plant nutrients were highly intertwined in that that excess of one factor alone cannot help to improve plant growth and yield. Singh et al. (2015) indicated that increased soil-water storage and its availability to crops at critical growth stages improves utilization of fertilizer and other farm inputs leading to improved water productivity in the dry lands. Increasing levels of fertilizer under moderate and good rainfall seasons, generally showed linear improvements in water productivity of maize while under low rainfall season (eg yr,1986), use of sufficient fertilizer even reduced WP below the recommended fertilizer application rate in the CRV condition. An understanding of interaction effects of soil water and nutrients is crucial for developing management strategies for achieving high yield and use efficiency of both water and nutrients in water-stressed regions.

4.3.3.2 Projected water productivity under different nutrient levels

Yield and water productivity simulated for Melkassa and Ziway under various nutrient application levels is presented in Table 4.4. Rain water productivity, which is a ratio of grain yield to actual evapotranspiration of the crop, was projected to be affected by the changing climate of the CRV of Ethiopia under unlimited nutrient conditions.

Table 4.4. Grain yield (Mg/ha) and water productivity (kg[yield]/ha per mm [ET]) in the baseline and projected periods under different levels of nutrient application

Period_RCPs	Melkassa							
	0-0 NP		23-20 NP		69-40 NP		120-60 NP	
	Yield	WP	Yield	WP	Yield	WP	Yield	WP
Baseline	3.8	6.3	5.1	8.1	5.4	8.4	5.6	8.7
Mid_RCP4.5	2.1	3.8	5	8.3	5.2	8.6	5.3	8.9
Mid_RCP8.5	1.6	3.0	5	8.3	5.2	8.7	5.3	8.9
End_RCP4.5	1.8	3.5	5	8.6	5.3	8.9	5.4	9.2
End_RCP8.5	1.0	2.1	4.6	7.9	4.7	8.2	4.8	8.4
	Ziway							
Baseline	0.2	0.6	3.8	8.6	4.7	10.7	4.7	10.7
Mid_RCP4.5	0.2	0.6	3.2	8.1	4.3	10.7	4.3	10.7
Mid_RCP8.5	0.2	0.6	3.0	7.8	4.1	10.6	4.1	10.6
End_RCP4.5	0.2	0.6	3.2	8.3	4.3	11	4.3	11
End_RCP8.5	0.19	0.7	2.4	6.9	3.6	10	3.6	10.1

The ensemble average climate scenarios showed considerable decline in water productivity (WP) on average by -9.5% (-11.5%, RCP4.5 to -8%, RCP8.5) and by 13.3% (-8%, RCP4.5

to -18.5%, RCP8.5) at Melkassa in the mid and end-century, respectively with respect to the baseline conditions. The change, however, was very minimal increase (+0.5% to +1%) for Ziway at both periods except a decline by 7.4% during end-century under RCP8.5 climate change scenario. Similarly, multi-model projections also projected declines in water productivity in most of the climate change scenarios in the CRV (Appendix Table 8 and Appendix Table 9).

All climate models, RCPs and future periods projected decline in water productivity ranging from -9.5% (ECEARTH-RCP8.5) to -13.6% (MPI-ESM-RCP8.5) and from -6.5% (CNRM-RCP4.5) to -23.2% (HadGEM2-ES-RCP8.5) at Melkassa in the mid and far periods, respectively. At Ziway site, however, the change in simulated WP will increase by +2.2% (ECEARTH-RCP8.5) and decrease in by -7.1% under HadGEM2-ES-RCP8.5 climate change scenario in the mid-century. Similarly, the end-century might benefit from the climate change in that WP might change in a range from +18.9% (CNRM-RCP4.5) to -13.3% under both HadGEM2-ES-RCP8.5 and MPI-ESM-RCP8.5 climate change scenarios. Positive changes were observed from models which projected increases in seasonal precipitation and conversely, the highest decline in precipitation also led to a drastic decline in water productivity under optimum nutrient application conditions.

Increasing nutrient application from 0-0 kg NP ha^{-1} to 120-60 kg NP ha^{-1} increased yield and water productivity under the considered climate change scenarios. Under similar climate scenario, increases in the nutrient level of the soil significantly improved grain yield and corresponding water productivity. During the baseline climate condition for example, application of 23-20, 69-40 and 120-60 kg NP ha^{-1} increased water productivity by 28.6, 33.3 and 38.1%, respectively as compared to no application of fertilizers at Melkassa. Similarly, increases from 23-20 kg NP ha^{-1} (average farmers' application rate) to 69-40 kg NP ha^{-1} increased yield by 5.9% and water productivity by 3.7%. Similarly, increases to 120-60 kg NP ha^{-1} level increased grain yield by 9.8% and water productivity by 7.4%. Furthermore, increases in nutrient content from 23-20 kg NP ha^{-1} to 69-40 kg NP ha^{-1} increased water productivity by 3.8% and to 120-60 kg NP ha^{-1} increased water productivity by 6.3% when the far period climate condition is considered.

The result showed that the typical value of water productivity calculated for the baseline year ranged from 6.1 to 9.8 kg ha^{-1} mm^{-1} under various levels of nutrient applications, and was in the range of 5-12.2 kg ha^{-1} mm^{-1} under optimum nutrition, which in both cases, were half of the average determined value for cereals. Passioura (2006) reported that the upper limit of water productivity of well-managed water-limited cereal crops is typically 20 kg ha^{-1} mm^{-1}. If the productivity is markedly less than this it is likely that major stresses other than water appear, such as poor nutrition and diseases (Passioura, 2006). In-line with this result, a water productivity in the range of 12–17.3 kg ha^{-1} mm^{-1} for maize was reported under water limited simulations in the CRV conditions (Getnet et al., 2016). However, the same authors indicated the actual farm water productivity was much lower in the CRV, ranging from 2.7 kg ha^{-1} mm^{-1} to 4.3 kg ha^{-1} mm^{-1} of the seasonal rainfall received for maize (Getnet et al., 2016). The low rate of fertilizer application coupled with low and variable rainfall probably reduced actual water productivity in the farmers' field. Furthermore, lower water productivity was also reported in some parts of the globe (e.g. rain-fed water use efficiency in China was 2.3 kg ha^{-1} mm^{-1}, far less than the potential; Deng et al., 2006).

Unfortunately, there is no genetic transformation, which likely improve water productivity and hence management mechanisms have been advocated to harness this trend. Consequently, Sharma et al (2015) recommended that small and timely irrigation along with management of soil nutrients can increase water use efficiency by 10-25%. Soil degradation, which is common in the CRV, is the major cause for nutrient depletion and loss of organic matter causing serious yield decline. Such depletions of nutrients and organic matter affects water availability for crops, due to poor rainfall infiltration, plant water uptake, and weak roots (Sharma et al., 2015) limiting water uptake and its productivity. The study revealed that increases in nutrient application showed improvements in water productivity by up to 38% under high input levels in the baseline year. Similar results were reported across the world (e.g., Singh et al., 2015). In multilocation water-balance studies in Niger, for example, fertilizer application increased WP in the range of 52 to 233% (Singh et al., 2015). Kathju et al. (2001) found that application of 80 kg N ha^{-1} significantly increased WP of pearl millet. At several field locations in China, N application also increased WP by about 20% (Deng *et al.,* 2004 cited in Singh et al., 2015)).

In the future periods, this finding clearly indicated projected decline in rain water productivity in the study area. Brouder and Volenec (2008) indicated that a 2.6 ℃ rise in average temperature in the US corn-belt could reduce water productivity by 11.5% which is proportional to the estimate at Melkassa where, a 2.1 ℃ rise in average temperature by mid-century (RCP8.5) reduced water productivity by 11%. Similarly, a 3.4 ℃ average temperature change from the baseline in the southern plains of US reduced water productivity by 17.3%, the estimate for the CRV of Ethiopia was 19% water productivity reduction for 3.7 ℃ average temperature deviation from the baseline.

Consequent to global warming, De Fraiture et al. (2007) indicated that the average annual agricultural evapotranspiration could double in the next 50 years leading to declines in water productivity unless technologies to increase yield are put in place. Contrary to the current findings, water productivity was reported to increase at increased CO_2 levels due to CO_2 fertilization (Manderscheid and Weigel, 2007; Brouder and Volenec, 2008) under conditions of sufficient soil moisture. However, Chartzoulakis and Psarras (2005) suggested that, although high CO_2 may improve plant water productivity, reduction in precipitation and increased evapotranspiration could reduce soil moisture in the changed climate, which hampers yield thereby reducing water productivity.

Kassie et al. (2014) reported the yield gain from increased CO_2 fertilization seems insignificant (+5.3 %) to contribute to improvements in water productivity in the study area. Similar report by Brouder and Volenec (2008) also indicated fertilization benefits of increased CO_2 are canceled out by yield losses because of increased temperature and water stress. The later authors also reviewed that transpiration of maize was reduced at high CO_2 level, and this plant exhibited only a modest increase in plant biomass. They showed that the total water use of maize was reduced when compared with ambient CO_2 due to closure of stomata in response to the reducing transpiration. Such shifts in water use might alter mass flow of nutrients to the root surface, change soil moisture patterns and increase foliage temperatures that could reduce photosynthesis, thus indirectly affecting yield and water productivity negatively. Increasing water productivity is particularly important where water is scarce compared with other resources involved in production.

In agreement with our findings, Brouder and Volenec (2008) reported declines in water productivity between 83% (Southern Great Plains) and 88% (Corn belt) regions of USA of current values by 2095 due to increases in temperature. Similarly, Guo et al. (2010) reported declines in maize yields and water productivity in northern China plain. Another study by Xiao et al. (2007) indicated a decrease in water productivity, length of growing period and yield in crops with increase in temperature under warming climate scenario. In contrary to our findings, Guo et al. (2010) observed a positive effect of CO_2 enrichment on yield and water use efficiency. They found increases of atmospheric CO_2 to 600 ppm, maize yields shown to increase by 12% and the water productivity improved by 25%, in comparison to those without CO_2 fertilization. However, other findings in contrary showed the fertilization benefits of increased CO_2 of the future period will be canceled out by yield losses because of increased temperature and water stress resulting in declines in water productivity (Brouder and Volenec, 2008; Kassie et al., 2015).

The declining trends of water productivity may foretell inevitable critical challenges on food security for developing countries in tropical regions for their ever increasing population (Berg et al., 2013). Zwart and Bastiaanssen (2004) also reported that the great challenge of the agricultural sector is to produce more food from less water, which can be achieved by increasing crop water productivity for the upcoming food demands. Pereira et al. (2002) indicated that the use of water for agricultural production in water scarce regions requires innovative and sustainable research and appropriate transfer of technologies. In line with this, Passioura (2006) suggested the requirement of cultivars and improved agronomic management to increase crop yield per unit of water and make utilization of CO_2 more effectively in producing biomass and convert more of the biomass into grain or other harvestable product.

4.3.3.3 Impact of climate variability and change on nutrient uptake and NUE

Nutrient uptake under different nutrient conditions

Water availability, water use and nutrient supply to plants are closely interacting factors influencing plant growth and yield. The results clearly indicated that nutrient uptake was affected by seasonal rainfall condition and levels of nutrient application at both locations (Figure 4.2) and initial nutrient content of the soil (Table 3.2). The cumulative uptake of both nutrients was higher for seasons with relatively high seasonal rainfall than in the low rainfall season. Accordingly, N uptake was, for example, reduced from 168 and 141 kg N ha^{-1} (high rainfall season) to 120 and 85 kg N ha^{-1} (low rainfall season) at Melkassa and Ziway, respectively under high application rate of NP (120-60 kg NP ha^{-1}). Similarly, cumulative P uptake was reduced from 36.2 and 28 kg P ha^{-1} (high rainfall year) to 25 and 12 kg P ha^{-1} (low rainfall year) at Melkassa and Ziway, respectively under similar P application rates.

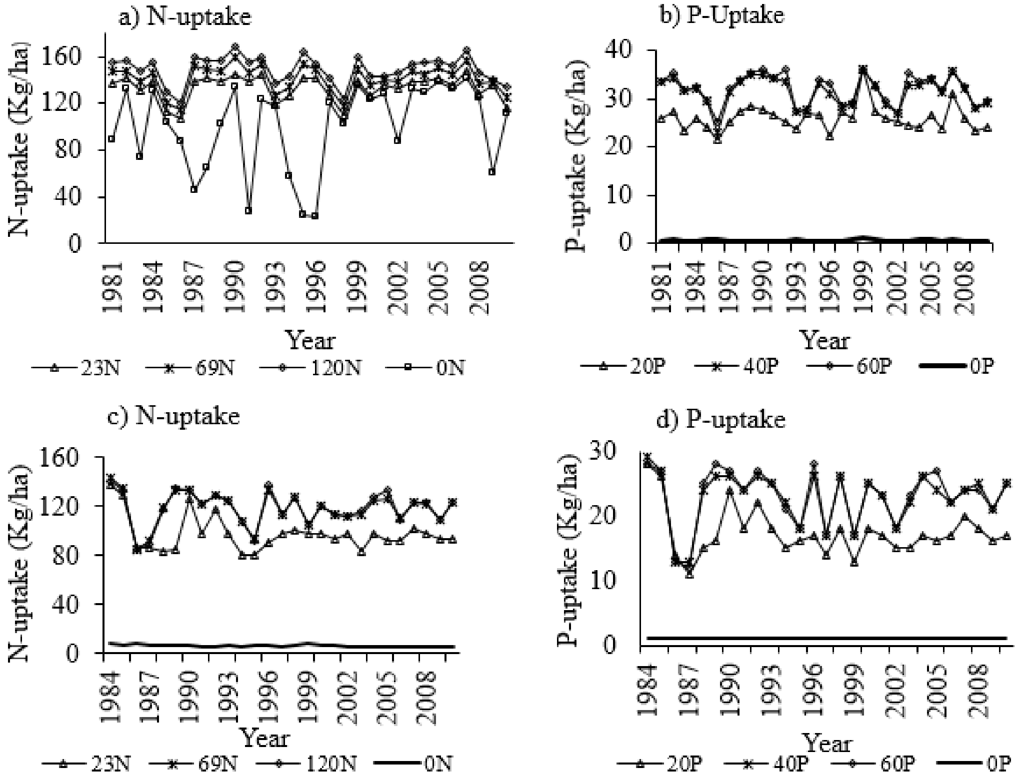

Figure 4.2. Cumulative seasonal N&P uptake of maize at Melkassa (a&b) and Ziway (c&d).

Relative changes in N&P uptake in the changed climate with respect to the baseline condition is presented in Table 4.5. The declining precipitation amount and increasing temperature in the study area likely affected nutrient uptake in the CRV during mid and far century. Phosphorus-uptake will be highly affected by the changed climate than N-uptake at both locations. Consequently, simulated changes in nutrient uptake were higher for low input application especially for P than when high input is applied. On the other hand, N-uptake at Melkassa showed a positive change except for the no input condition which might be related to increased time of availability of N in the soil due to limited solubility and leaching resulted by the reduced soil moisture in the changed climate. Conversely, the decline in precipitation and corresponding increase in temperature reduced P-uptake through the limited P solubility under low soil moisture condition. However, the reduced availability of P for uptake in the changed climate can be offset by optimum phosphorous application. The significant decline in nutrient uptake will pose a challenge to the future rainfed agriculture.

Table 4.5. Changes in seasonal N &P uptake in the future periods relative to baseline using ensemble average of four climate models' climate scenario

Period_RCP	N-uptake (%)				P-uptake (%)			
	0-0 NP	23-20 NP	69-40 NP	120-60 NP	0-0 NP	23-20 NP	69-40 NP	120-60 NP
					Melkassa			
Mid_RCP4.5	-8.2	1.4	1.6	-0.1	-10	-16	-2.4	-4.3
Mid_RCP8.5	-13.3	1.5	3	1.3	-20	-19.9	-3.5	-3.1
End_RCP4.5	-12.2	2.4	3.3	-0.1	-20	-16.6	-1.5	-2.8
End_RCP8.5	-27.6	-5.8	2.5	-0.8	-40	-34.7	-9.7	-9.4
				Ziway				
Mid_RCP4.5	0	-8	-12.7	-10.9	0	-14.5	-12.2	-9.5
MId_RCP8.5	-10.4	-5.1	-14.3	-12.9	-20	-14.5	-12.6	-11
End_RCP4.5	2.1	-6.3	-12.1	-12.6	0	-15.2	-10.9	-10.6
End_RCP8.5	-14.6	-13.5	-23.5	-23.2	-20	-20.7	-21.4	-22

The uptake of N and P differed with rate of their application regardless of the season and location (Figure 4.2). Initial nutrient content (N and P) of the soil at both locations was presumably low where nutrient uptake is negligible under no nutrient application regardless of rainfall variations. However, increasing the level of nutrient application in such low fertility soils showed increases in nutrient uptake. Under low nutrient fertility soils, nutrient uptake could be primarily influenced by the level of nutrient applied and the rainfall amount received. Sharma et al. (2015) reported decreases in nutrient uptake of P when the soil moisture level decreased regardless of the fertility status of soils. Increasing application rate of fertilizer from 23/20 kg NP ha^{-1} to 120/60 kg NP ha^{-1}, on average, improved N uptake by 12.2 and 21.7% at Melkassa and Ziway, respectively. Similarly, the P uptake was considerably improved by about 23.1 and 211% at Melkassa and Ziway, respectively due to application of the same rate. The findings generally indicate that high rainfall and increasing level of nutrient improved nutrient uptake by maize in the CRV condition, which might be related to increased root zone moisture that is conducive for uptake.

Given that soil moisture and temperature are the primary determinants of nutrient availability, root growth and development and that carbon allocation to roots governs nutrient acquisition, it is reasonable to expect the outcomes of the process will be reflective of the climate condition (Brouder and Volenec, 2008). On the other hand, increases in air temperature and variabilities in precipitation, significantly impact the prevailing root zone temperature and moisture regimes (Brouder and Volenec, 2008). Consequently, changes in plant water use or decline in water availability was reported to significantly alter nutrient uptake and possibly increase tissue temperatures (Brouder and Volenec, 2008).

Similar report by Sharma et al. (2015) indicated that root zone soil moisture reduction in soil water potential from -233 to -2170 kPa reduced P-uptake by 42 and 40% in a low- and high-P fertility soil, respectively. The same study also indicated that reduction in moisture content reduced root surface area by 50 and 32% under low and high P soil condition, respectively, affecting nutrient uptake negatively. Brouder and Volenec (2008) also claimed that increases in root surface area increase nutrient uptake considerably. Likewise, Lynch and St Clair (2004) noted that under conditions of reduced transpiration, acquisition of nutrients that travel from bulk soil to the root surface primarily by mass flow will be negatively affected, resulting in nutrient deficiency and uptake. Similarly, under projected climate, increases in air temperature and changes in precipitation will significantly impact prevailing root zone temperature and moisture regimes. Changes in plant water use or reductions in water availability may significantly alter nutrient uptake and possibly increase tissue temperatures (Brouder and Volenec, 2008).

Nutrient use efficiency (NUE) of maize in the CRV

Baseline climate scenario

The results showed that all nutrient efficiency indicators showed a higher value of nutrient use efficiency (NUE) at low fertilizer application rates (23/20 kg N/P ha^{-1}) than the corresponding high applications of fertilizer (120/60 kg N/P ha^{-1}) (Table 4.6). The Agronomic efficiency of N (AE-N) was estimated on average as 36.5 and 21.5 kg kg^{-1} through application of 69 and 120 kg N ha^{-1}, respectively. Similarly, the simulated AE-P was, on average, 63 and 43 kg kg^{-1} under the application of 40 and 60 kg P ha^{-1}, respectively.

Thus, it can be deduced that N and P applications above 69 kg N ha^{-1} and 40 kg P ha^{-1} would not improve yield under the current climate and management condition in the CRV as also confirmed by the nil - to insignificant yield increase. This shows that increasing nutrient level alone would not improve agronomic efficiency under the current climate condition. Improving water availability through *in-situ* conservation or application of irrigation water might improve agronomic efficiency in cases of increased fertilizer application. In line with this, Mohammed et al. (2016) reported higher maize grain yield under irrigated condition than when irrigation was not provided at the same high amount of applied fertilizer in Ethiopia.

Table 4.6. NUE as affected by levels of NP application in the CRV during 1981-2010

NUE	N- rate (kg ha^{-1})			P- rate (kg ha^{-1})		
	23	69	120	20	40	60
AE (kg kg^{-1})	108 (0-213)	36.5 (0-75)	21.5 (0-46)	124.5 (0-245)	63 (0-130)	43 (0-92)
RE (%)	269 (9-513)	111 (14-186)	67 (12-116)	104.5 (104-174)	65 (55-87)	44 (40-60)
PE (kg kg^{-1})	35 (0-127)	32 (12-83)	32 (13-71)	140 (0-206)	103 (0-155)	100 (0-163)
PNB	5 (3.5-6.4)	1.9 (1.2-2.3)	1.1 (0.7-1.4)	1.1 (0.6-1.8)	0.7 (0.3-0.9)	0.45 (0.2-0.6)

Values in the bracket indicate the minimum and maximum values recorded during the simulation period

Apparent recovery efficiency (RE) is also another short-term measure of NUE of applied nutrients. It was estimated under 69/40 kg N/P ha^{-1} application rate, whereby each kilogram of added nutrient, on average, increased N and P uptake by 1.11 and 0.65 kg, which were equivalent to the recovery efficiency of 111 and 65%, respectively (Table 4.6). Increases in the application rate of fertilizer to 120-60 kg NP ha^{-1}, reduced uptake of N and P by 0.67 and 0.44 kg, respectively showing that the recovery efficiencies were 67 and 44% for N and P, respectively. In general, P recovery efficiencies were lower than that of N at each nutrient level. Recovery efficiency value is usually an important indicator for environmental pollution monitoring by excess of nutrients. High RE indicates low loss to the environment (reduced chance of eutrophication etcetera) while low RE can be explained by increased losses in economic or environmental terms.

Physiological efficiency (PE), which is a measure of yield increase per unit nutrient uptake, was higher for P than N in the CRV. Changes in nutrient application level did not change PE for both nutrients. The simulation result indicated 32 and 100 kg of grain yield per unit uptake of N and P, respectively. Partial nutrient balance (PNB), which is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use") showed differences among the different rates of fertilizers used and season. Partial nutrient balance for N (PNB-N) of more than 1 was computed at the lower N rate (23 kg N ha^{-1}) as compared to the higher N rates indicating higher N mining and looming soil deficiency of N at this level of fertilizer addition. The recommended N rate (69 kg N ha^{-1}) also showed considerable N removal (PNB=1.9), which should be replenished to the soil. The highest rate of N (120 kg N ha^{-1}), however, resulted in an estimated PNB close to one suggesting soil fertility will be sustained at a steady state.

The estimated partial nutrient balance for P (PNB-P) on the other hand, was around unity (1) for the low P application rate while values less than unity were estimated for the higher P application rates. Under high P application, there exists avoidable P loss to the system, and hence actions to improve NUE could be suggested. In general, mechanisms that could improve nutrient availability and optimum fertilization would greatly improve nutrient uptake and corresponding yield in the CRV of Ethiopia. The wide range of each NUE indicator within similar application rates, on the other hand, suggests the existence of variations due to seasonal rainfall variabilities. Accordingly, NUE was low at each fertilizer levels during seasons of low rainfall and the higher values were usually related to high rainfall seasons.

Future climate scenario

Under the selected measures of nutrient use efficiency indices, NUE might decline in the future climate scenarios as compared to the baseline climate condition (Table 4.7 and Table 4.8). In many countries, limited water is a major impediment to effective crop nutrient uptake and use efficiency, while nutrients are often the most limiting factors to water productivity in humid zones (Thomason et al., 2015). The projected declines in precipitation and elevated temperature in the study area will be expected to reduce water availability that in-turn will have a negative consequence in resource use efficiency in the future. Change in NUE was in general higher RCP8.5 than RCP4.5 at both periods and locations. Similarly, all NUE indices showed the progressive decline in nutrient use efficiency across future time periods.

Interestingly, under all NUE indices, climate scenarios, periods and locations except for apparent recovery efficiency (RE), progressive decline in nutrient use efficiency were observed as NP application is increased from 23-20 kg NP ha^{-1} to 120-60 kg NP ha^{-1}.

Nitrogen Use Efficiency (N-UE)

Projected changes in N use efficiency of maize under changed climate scenario is presented in Table 4.7. The short-term indicator agronomic efficiency (AE) showed declines in productivity improvement at any added N due to climate change. The relative decline in productivity improvement by increasing application of N is generally higher under RCP8.5, end century and at Ziway than the corresponding RCP, period and at Melkassa condition.

Table 4.7. Simulated changes in N-UE under varying N level relative to baseline period

NUE	N-rate (kg N ha$^{-1)}$	Melkassa				Ziway			
		Mid4.5	Mid8.5	Far4.5	Far8.5	Mid4.5	Mid8.5	Far4.5	Far8.5
AE	23	-6.8	-10.5	-8.6	-17.3	-8.3	-11.1	-9.3	-20.4
	69	-9.2	-12.3	-10.8	-23.1	-7.7	-9.6	-7.7	-26.9
	120	-10.5	-13.2	-13.2	-23.7	-6.7	-10	-6.7	-26.7
RE	23	1.8	3.6	3.6	-3.6	-8.8	-2.9	-5.9	-11.8
	69	0	5	5	5	-16.7	-16.7	-16.7	-27.8
	120	0	0	0	0	-9.1	-18.2	-18.2	-27.3
PE	23	-6.4	-10.6	-8.5	-17	-9.4	-12.5	-9.4	-21.9
	69	-8.1	-13.5	-10.8	-21.6	-6.7	-10	-10	-26.7
	120	-11.4	-14.3	-11.4	-22.9	-7.1	-10.7	-7.1	-28.6

The result indicates N response will likely decline in the future geared by declining precipitation and escalating temperature affecting the moisture level in the CRV maize growing areas. Despite decrements in N use efficiency in short and long-term productivity improvement of the cropping system, the climate change seems to be not contributing to the loss of N from the cropping system at Melkassa. However, at Ziway N- Loss from the cropping system is evident under all climate scenarios and periods where the highest loss of N is expected in the far period under RCP8.5 climate scenario. Such loss of N from farmlands of Ziway might affect the nearby lakes through eutrophication which can be regarded as the indirect negative effect of the changing climate.

The physiological ability of the plant to transform nutrients acquired from the source applied in to economic yield (PE) is also affected by the changing climate. It is very related that periods and RCPs with the highest changes in temperature showed the highest declines in physiological efficiency of maize in the CRV. The increase in average temperature for example by 2.1 °C will decrease N-PE by 10.6% and 3.72 ^{0}C will decrease N-PE by 17% under current local rate from the baseline conditions at Melkassa. Similarly, 2.3 °C increase from the baseline decreased N-PE by 12.5% and increase of 3.94 °C decreased N-PE by 21.9% at Ziway. Heat stress seems to affect the physiology of maize related to N-uptake and translate it to economic yield.

Phosphorus Use Efficiency (P-UE)

Projected changes in P use efficiency of maize under changed climate scenario are presented in Table 4.8. The agronomic efficiency (AE) might be negatively affected in the future by up to 26.7% and the effect is highly felt as the fertilizer rate is increased. The increase in yield expected from a unit addition of P might decrease in the mid and end century at both locations and RCPs. Similarly, the high input systems (Supplied with 60 kg P ha^{-1}) seem to be highly affected in the future time periods than the low input systems (supplied with 20 kg P ha^{-1}). At the high emission scenario (RCP8.5), at Melkassa for instance agronomic efficiency of P projected to decrease by 9.7 (low input system) to 15% (high input system) in the mid period. Similarly, in the end of century, the likely decline in efficiency might rise by 16.7% and 24.7% in the low and high input systems, respectively with respect to the baseline conditions.

Table 4.8. Simulated changes in P-UE under varying P level relative to baseline period

NUE	P-rate (kg P	Melkassa				Ziway			
		Mid4.5	Mid8.5	End4.5	End8.5	Mid4.5	Mid8.5	End4.5	End8.5
AE	20	-6.5	-10.8	-8.1	-16.7	-8.1	-10.5	-8.9	-20.2
	40	-9.7	-13.3	-11.5	-23	-7.8	-10	-7.8	-26.7
	60	-11.7	-15.6	-13	-24.7	-6.7	-10	-8.3	-26.7
RE	20	-18.8	-18.8	-18.8	-37.5	-14.3	-14.3	-14.3	-14.3
	40	0	0	0	0	-16.7	-16.7	-16.7	-16.7
	60	-16.7	0	0	-16.7	0	0	0	-25
PE	20	-6.8	-10.5	-8.3	-16.9	-9	-11.2	-9	-20.2
	40	-9.3	-13.4	-11.3	-23.2	-7.7	-10.3	-8.4	-27.1
	60	-11	-15.1	-12.8	-25	-7.4	-9.6	-8.1	-26.7

The decline in agronomic efficiency might be related to low uptake of P under diminishing rainfall and increased temperature in the future time periods. Sharma et al. (2015) indicated reduction in moisture content due to climate change reduced root surface area by 50 and 32% under low and high P soil condition, respectively, affecting nutrient uptake and AE negatively. The same authors also indicated that root zone soil moisture reduction in soil water potential from -233 to -2170 kPa reduced P-uptake by 42 and 40% in a low- and high-P fertility soil, respectively. Improving water availability through in-situ conservation or application of irrigation water might improve agronomic efficiency in cases of increased fertilizer application. Mohammed et al. (2016) reported higher maize grain yield under irrigated condition than when irrigation was not provided at the same high amount of applied fertilizer in Ethiopia.

The apparent recovery efficiency (RE) of P, will likely, in most cases, not be affected by the changed climate especially in the high P input systems. The low P input systems, however, will experience significant losses (-14% to -37%) in the recovery efficiency under the changed climate. The higher negative value in RE indicates high uptake condition in the baseline period than the changed climate condition. Under such conditions, considerable concentration of P remains in soil and gradually be lost through erosion creating risk impacts to water and air resources and also lowers economic returns to farmers in the changed climate. Low moisture condition due to climate change reduces nutrient uptake which could suppress apparent recovery efficiency. Similarly, reduced uptake of P was reported under reduced moisture condition which might have led to reductions in apparent use efficiency under low and high-P fertility soil (Sharma et al., 2015).

The ability of maize to transform P added to the soil in to economic yield (PE) will also drastically reduce due to the climate changes. The high temperature coupled with declining rainfall amounts seems to affect the physiology of maize to efficiently acquire, assimilate and transform P in to grain yield. The physiological effect of climate change on maize to transform P in to grain yield was projected to change in the range of -6.2 to -20.2% for low P input systems and from -7.4 to -26.7% for high P input systems in the CRV of Ethiopia.

Our estimates for the different NUE indicators were high at low fertilizer application levels than at high application rates indicating that the fertility level of the experimental soils was below the fertilizer requirement threshold. Fixen et al. (2015) reported high AE and RE measurements when soil fertility status was well below critical levels, and the values rapidly declined as soil fertility increased. Sustainability is associated however with the intermediate AE and RE values observed when rates applied are close to removal, and soil fertility levels are maintained near the critical level.

The NUE estimates in the present study are generally in agreement with other globally published estimates reviewed by Ladha et al. (2005). For instance, Ladha et al. (2005) reported NUE estimates for maize as AE = 24 kg kg^{-1}, RE about 65% and PE around 37 kg kg^{-1}, which are comparable with our findings (21.5 kg kg^{-1}, 67% and 32 kg kg^{-1}, for AE, RE and PE, respectively). The results also did not deviate from the average NUE estimates for maize reported by Ladha et al. (2005) for Africa (14 kg kg^{-1}, 63% and 23 kg kg^{-1}). Similar results were also reported for RE, 57% by Sheldrick et al. (2002), 56% by Howarth et al. (2002) and 52% by Janzen et al. (2003).

Regarding sustainability of the fertility status of soil with the nutrient management, our findings showed that PNB-N was greater than unity while PNB-P was on the contrary (Table 8). Values well below unity, where nutrient inputs far exceed nutrient removal, might suggest avoidable nutrient losses and thus the need for improved NUE (Fixen et al., 2015) under the CRV conditions, although attainable values are cropping system and soil specific. A partial nutrient balance greater than unity indicates higher removal of nutrients with the harvested crop than the amount applied by fertilizer and/or manure, a situation equivalent to "soil mining" of nutrients (Fixen et al., 2015). This situation may be desired, if available nutrient contents in the soil are higher than recommended. In cases where soil nutrient concentration is at or below recommended levels, however, a PNB >1 must be regarded as unsustainable (Brentrup and Pallière, 2010). Over the short term and on individual farms, PNB can show substantial fluctuations due to cash flow and market conditions, especially for P and K, suggesting the importance of longer-term assessment of PNB over several years.

Studies indicated that only 15-30% of applied fertilizer P is taken up by crops in the year of its application (Syers et al., 2008). Thus, potentially large gains in P use efficiency can be made by improving P acquisition (Veneklaas et al., 2012). Despite the yield benefits, increasing P uptake alone will increase total amounts of P exported from the field. Increased

P exports can cause considerable off-site environmental problems (Tiessen, 2008; Childers et al., 2011), and should be replaced with additional fertilizer to avoid soil P depletion in the long term. The most sustainable and productive agricultural systems will be those where P exports are balanced by P inputs, and which have high yields per unit P taken up, that is, they have high PUE (Veneklaas et al., 2012). Improving the efficiency of phosphorus (P) fertilizer use for crop growth requires enhanced P acquisition by plants from the soil (P-acquisition efficiency) and enhanced use of P in processes that lead to faster growth and greater allocation of biomass to the harvestable parts (internal P-use efficiency (PUE) (Veneklaas et al., 2012).

The study indicated that under drying future conditions, all nutrient efficiency indicators showed declines in efficiency with respect to the baseline climate conditions. Changes in rainfall amount and linear increases in temperature seems to affect the long-term productivity of both the low and high P input cropping systems negatively in the CRV of Ethiopia. It could be evident that the dry future periods will likely reduce nutrient availability, thereby affecting nutrient uptake of crops. Similar to our result, Ryan et al. (2010) indicated crop responses to N were the highest where rainfall was favorable (350-500 mm) and minimal when rainfall was below 250 mm where the changing climate will likely reduce the rainfall amount. It can also be related that, with increase in water supply up to a certain point, it improves fertilizer-use efficiency by increasing the availability of applied nutrients. Besides, to avoid the application of excess fertilizer during the years of low rainfall, strategies such as ‘response farming’ which use early rainfall events to decide the amount of fertilizer for the approaching season and adjusting split fertilizer applications to the expected rainfall events, need to be advocated.

4.4 Conclusions

Climate change is projected to affect maize yield and resource use efficiency in the central rift valley of Ethiopia. Considerable yield loss was simulated in the future periods for both limited and unlimited nutrient conditions under rainfed and irrigated maize production systems in the CRV. Projected increase in temperature coupled with reductions in rainfall contributed to the high yield reductions implying greater risks of crop production in the future. The simulated yield of irrigated maize was also affected by the climate change despite unlimited water provision implying heat stress could also pose tremendous challenges in the future. Water productivity and nutrient use efficiency were reduced tremendously in the future period due to climate change. Such reductions in resources use efficiency will have implications on the environment, economy and farmers livelihood in the region. Improving water availability through in-situ conservation or application of irrigation water might improve water and nutrient use efficiency with application of optimum fertilizer. Besides, increased warming in the future period necessitates development of heat resistant cultivars through breeding for CRV conditions.

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CHAPTER FIVE

General Summary and Conclusions

5 General Summary and Conclusions

5.1 Summary

Climate variability and change are amongst the most important environmental challenges of the 21St century. The global average temperature has increased by 0.74 ^{o}C in the last century and is projected to increase with 1.1-5.8 ^{o}C by the end of this century and the rainfall patterns is estimated to change with an increased frequency of extreme events. Anthropogenic factors such as emission of greenhouse gases and changes in land use and land cover have contributed to the current change. Ethiopia's food crops and livestock upon which the livelihoods of millions depend are underpinned by its natural resources –land, water and forests. In the face of growing climate change threats, such as temperature rise, frequent droughts and flooding, Ethiopia would be more vulnerable due to strong reliance of climate risk sector, agriculture.

This research investigated the characteristics of the different agroclimatic indices related to the underlying challenges of rainfed agriculture in the GRVB for the current and projected periods, estimated climate induced yield level, variability and gap of maize crop and assessed impacts of climate variability and change on water productivity and nutrient use efficiency in the semi-arid drought prone lowlands of the central GRVB.

The different agroclimatic indices were used to assess the annual and seasonal rainfall characteristics of the GRVB in-relation to rainfed agriculture for the current and projected periods. In the baseline condition, station-based analysis indicated higher variation of rainfall during both *Belg* and *Kiremt* seasons for the majority of stations. The short season however was very unreliable to crop agriculture than the main season. Time series analysis of annual and seasonal rainfall revealed a non-significant trend except at Melkassa and Gewane where a significant increase ($P<0.05$) was observed. Mean potential onset dates ranged from March 23 at Jimma to June 15 at Melkassa and exhibited high annual variations. On the other hand, mean dates of cessation vary from August 9 to November 17 in the GRVB. Length of the growing period of the main season spatially varied from as low as 20 in the northeastern lowlands to as much as 236 days in the southwestern parts of the study region. A non-significant increasing trend of LGP were observed in the majority of stations. Debresina, however, showed a significant ($P \leq 0.1$) declining trend in LGP equivalent to 10 days per decade signaling shrinks in season length that could affect rainfed agriculture. The probability of occurrence of dry spell for 5 consecutive days is more common in the semiarid and arid lowlands while 3 days dry spell is common in all agroecology studied. Moreover, seasonal water deficit varied for maize depending on variety, time of planting and season which could contribute to significant yield reduction to complete crop failure in some of the years in those areas.

The study estimated increases in temperature on average by +0.7 to +1.25 ºC (RCP4.5) and +0.9 to +1.6 ºC (RCP8.5) while it may likely rise up to +4 to +6 ºC in the mid and far periods, respectively. Similarly, changes in rainfall were estimated by +4.2 to -16% (RCP4.5) and +3.8 to -18% (RCP8.5) across the basin in the near future periods. A corresponding change in LGP from -5.66 to -25.5% and +3.9 to -16.4% was also simulated for central semiarid areas and central sub-humid highlands, respectively. On the other hand, HadGEM2-ES_RCA4 model simulations revealed that slight increases in dry spell length under near, mid and far periods and two emission scenarios. The relative increases in dry spell length are higher for currently cooler sub humid and humid environments such as Assela (1.84 to 5.34%) and Jimma (from 0 to 1.02%) than the semi-arid lowlands like Melkassa (0.12%). Seasonal water requirement satisfaction for early, medium and late maturing maize cultivars showed a substantial decline in the near, mid and end of century simulation under each emission scenario across all agroecology.

The observed climatic variability and trends were then assessed for its impact on yield variability, yield gap and related resource use efficiency in the region. The risks were evaluated under different nutrient application under both irrigated (non-water limited) and rainfed (water limited) farming systems in the semi-arid central rift valley areas using different statistical methods and crop model-based estimations. The result revealed high and positive correlation between rainfall and maize grain yield ($r=0.67$ at Melkassa and $r = 0.69$ at Ziway) in the CRV while day temperature affected grain yield negatively ($r= -0.44$) at Ziway ($P \leq 0.05$) during the simulation period. Variation in total seasonal rainfall at Melkassa and Ziway explained 44.9 and 48.5% of the variation in yield respectively, under optimum nutrition. Following variation in rainfall, high yield variability (CV=23.5%, Melkassa and CV=25.3%, Ziway) was observed for optimum nutrient simulation than the corresponding nutrient limited simulation (CV=16%, Melkassa and 24.1%, Ziway) in the baseline period. The observed farmers' yield was by far lower by 28, 48 and 57% of the researcher-managed, water-limited and potential yield of the crop, respectively, indicating wide maize yield gap in the region. Water productivity and nutrient use efficiency were higher during high rainfall years and with high nutrient levels than during low rainfall years. However, increasing levels of fertilizer during low rainfall years did not improve grain yield, water productivity and nutrient use efficiency.

Climate change impact on maize yield and future resources use efficiency were assessed using DSSAT-CSM crop model under eight climate scenarios for mid and far periods. Potential yield of maize (irrigated) might decrease on average by 16.5% under RCP4.5 and by 20% under RCP8.5 relative to the baseline period due to climate change by mid period. On the other hand, rainfed maize yield might also be negatively affected on average by 12.5% under both RCPs by in the same period. The decline in yield seems continue to escalate in the far century by 9.5%, RCP4.5 and 23.5%, RCP8.5 climate scenario. While the negative impact of climate change on maize yield is very likely, the extent of the yield impact is more uncertain (ranging from 0 to -31%) between climate models used in the CRV condition. Maize yield is reduced even for wet scenarios (that predict an increase in rainfall) implying that the impact of increased temperature is more pronounced than rainfall under climate change. Water productivity change was simulated in the range from 0 to -3.1% and +1 to -10.3% at Melkassa during mid and far centuries with respect to the baseline. In similar token, significant number of the climate models simulated declines in productivity of water up to 2.2% during mid and 13.3% in the far century at Ziway. Nutrient uptake and corresponding Nutrient Use Efficiency (NUE) are also negatively affected by climate change. P uptake decreased in the CRV on average by 14.5 to 18% by mid period while N uptake didn't show significant changes at Melkassa. N use efficiency indicators showed decreases in the range from 8.5 to 10.5%, by mid period. Similarly, P use efficiency also decreased in the range between 9.3 to 10.5% during the same period. The interaction of water availability and nutrient application positively increased both water productivity and nutrient use efficiency under changed climate.

5.2 Conclusions

Current and future trends of declining rainfall amount, declines in the length of the growing seasons and increasing lengths and frequency of in-season dry spells coupled with increasing temperature generally create increasing risks for rainfed crop production in the GRVB. Shortened growing seasons due to a late start of rainfall and early cessation hampers soil preparation and exposes crops to increased terminal moisture stress during grain filling, reducing crop yields. In addition, it could affect production of well adapted medium and late maturing cultivars in areas where supplementary irrigation is unavailable. The increasing temperature on the other hand will increase the rate of evapotranspiration and crop water requirements, adding to the currently frequent water stress of crops in the relatively drier parts of the GRVB. Rainfed crop production in the region, which is already impacted by the current climate variability, is likely to be further challenged with future climate change. Consequently, the majority of the stations in the GRVB may suffer from reduced water availability in the future, which will potentially harm the predominant rainfed based farming of the area.

Climate induced yield variability, an incomparable yield level and wide yield gap in the CRV imply potential yield improvements through use of optimum inputs. Moreover, in areas where rainfed farming is dominant, co-managing fertilizer and available water could improve production of maize two folds, while water or nutrient alone does little improvement in maize yield. The study concludes presence of such huge yield gap from what the environment could potentially offer imply that, use of proper inputs (irrigation, optimum fertilizer) could dramatically improve yield by more than double and contribute to ensure food security in the country. The climate change is also posing further challenges to rainfed agriculture in the GRVB of Ethiopia. Decreased rainfall amount may hinder maize yield in the future period. Simulated declines in irrigated maize yield in the future periods might also suggest the pressing challenges of increasing temperature impact on the current cultivar affecting crop production in the region. Decreases in RUE as a result of climate change might imply potential risks of environmental deterioration in the future.

5.3 Recommendations

- The current high dependence of seasonal rainfall and yield could signify the importance of other water sources for dependable agriculture in the region. Development of irrigation schemes for areas where surface water for irrigation is available could be recommended. Similarly, High level of climate variability and change coupled with increasing trends of temperature likely resulted in seasonal moisture deficit that could explain to low yield levels in the region. The study suggests, co-management of fertilizers and supplementary irrigation water could significantly boost crop production which could ensure food security in the region.

- Declines in water productivity and nutrient use efficiency due to increased temperature in the future period trigger application of improved water management in place. Likewise, maize breeders should also focus to develop heat tolerant varieties which can cope the ever-increasing temperature of the CRV to sustain maize production in the area.

- In countries like Ethiopia where long term experimental data are scant, crop models provide reliable estimates of relationships of edaphic factors of production and crop productivity in the variable faces of climate. Hence, crop simulation studies should be encouraged to avail science-based evidences to inform policy makers develop sound policies to tackle climate change. Such modeling approaches should also be further applied to quantify the risks and identify potential adaptation options associated with climate change for the different crops and agroecology in the study area. The study highly recommends, application of two or more crop models to estimate modeling uncertainties and compare results among models to provide necessary decisions pertaining climate induced risks of crop production in the region.

Appendices

Appendix Table 1. Model comparison for annual and seasonal precipitation of the GRVB for impact assessment

Model	Annual			*Kiremt*			Remark
	R^2	MAE	RMSE	R^2	MAE	RMSE	
CNRM-CM5_RCA4	0.59	197.6	78	0.42	231.5	88.3	
EC-EARTH_RCA4	0.54	147.7	68.7	0.19	247.7	91.6	
HadGEM2-ES_RCA4	0.55	141.3	68.6	**0.62**	234.9	80.7	Selected
MPI_ESM-LR_RCA4	0.56	177.5	72.7	0.19	247.6	92.1	
CNRM-CM5_ClmCom	0.43	154.1	67.2	0.13	252.6	91.1	
EC-EARTH_CLMCom	0.42	158.9	67.6	0.13	251.5	90	
HadGEM_CLMCom	0.39	174	72.1	0.47	266.6	96.2	
MPI_ESM-LR_CLMCom	0.43	141.1	67.1	0.13	252.9	91.5	
Ensemble_RCA4	**0.74**	149.6	59.2	0.33	293	102.1	Selected
Ensemble_ClmCom	0.43	146.4	66.9	0.18	270.5	98.5	
Ensemble_All	0.53	127.1	66.3	0.26	275.2	99.7	

Appendix Table 2. Model comparison for annual and seasonal temperature of the GRVB for impact assessment

GCM_RCM	Annual			*Kiremt*			Remark
	R^2	MAE	RMSE	R^2	MAE	RMSE	
CNRM-CM5_RCA4	0.88	7.24	1.89	0.94	5.55	1.46	Any model can be used for simulating the future temperature of the basins
EC-EARTH_RCA4	0.88	7.24	1.89	0.93	5.29	1.41	
HadGEM2-ES_RCA4	0.88	7.22	1.88	0.94	5.57	1.46	
MPI_ESM-LR_RCA4	0.88	7.24	1.89	0.94	5.54	1.45	
CNRM-CM5_ClmCom	0.88	7.24	1.89	0.94	5.57	1.46	
EC-EARTH_CLMCom	0.88	7.24	1.89	0.93	5.29	1.41	
HadGEM_CLMCom	0.88	7.22	1.88	0.94	5.58	1.46	
MPI_ESM-LR_CLMCom	0.88	7.24	1.89	0.94	5.55	1.46	
Ensemble_RCA4	0.88	7.23	1.89	0.94	5.49	1.44	
Ensemble_ClmCom	0.88	7.23	1.89	0.94	5.5	1.44	
Ensemble_All	0.88	7.23	1.89	0.94	5.49	1.44	

Appendix Table 3. Percentage changes in monthly and annual rainfall as projected by different Global Climate Models (GCMs) downscaled by RCA4 RCM for two emission scenarios for the 2071 - 2100s relative to the baseline period (1981-2010) at Melkassa

Month	CNRM		ECEARTH		HadGEM2-ES		MPI-ESM	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Jan	61	52	14	-6	-84	-87	-38	-22
Feb	-10	-8	-47	-44	-81	-67	-29	-66
Mar	-6	-39	18	9	-84	-72	-18	-48
Apr	2	-19	-20	-14	49	42	-20	-33
May	19	14	-42	0	-6	86	-22	-32
Jun	-7	-4	-20	-15	+264	+312	-2	-28
Jul	11	-7	5	7	+200	+129	-9	-10
Aug	7	-5	4	-4	+119	+111	-1	-6
Sep	-5	7	-3	-7	+32	21	3	-7
Oct	36	11	13	69	-15	-26	57	57
Nov	-25	11	-22	-29	-65	-56	56	66
Dec	-29	-52	1	25	-78	-86	-63	36
Annual	**6**	**-4**	**-5**	**-2**	**-21**	**-24**	**-6**	**-14**

Appendix Table 4. Changes in monthly and annual rainfall as projected by different General Climate Models (GCMs) downscaled by CLMcom RCM for two emission scenarios for the 2071 -2100s relative to the baseline period (1981-2010) at Melkassa

Month	CNRM		ECEARTH		HadGEM2_ES		MPI-ESM	
	RCP45	RCP85	RCP45	RCP85	RCP45	RCP85	RCP45	RCP85
Jan	-30	-24	-39	-58	-86	-70	-48	-49
Feb	-1	-18	-25	-64	-77	-76	-49	-63
Mar	-47	-68	-40	-55	-61	-51	-16	-41
Apr	-12	-32	-16	-22	+31	+73	-29	-50
May	-23	-5	-14	-33	+67	+35	-16	-29
Jun	-3	-11	-7	-10	+108	+92	-8	-42
Jul	0	4	-6	-8	+103	+93	-4	6
Aug	7	4	-3	-15	+69	+76	-1	6
Sep	-8	-8	1	7	+23	+6	-4	-17
Oct	5	-15	15	27	-30	-41	-10	0
Nov	-33	30	41	-3	-63	-66	37	26
Dec	8	-17	10	-22	-83	-70	32	-42
Annual	**-7**	**-10**	**-9**	**-16**	**-25**	**-24**	**-10**	**-17**

Appendix Table 5. Modelling approaches of DSSAT CERES-Maize crop model

Processes	**DSSAT CERES-Maize**
Crop phenology	Function of temperature, photoperiod
Leaf area development and light interception	Simple: Leaf area expansion is driven by temperature as a function of leaf number and assimilate availability
Light utilization	Descriptive (simple) radiation use efficiency approach. Constant radiation use efficiency is used to directly convert absorbed radiation into dry matter.
Dry matter accumulation	Driven by temperature as a function of phenology, limited by assimilate availability, excess assimilate partitioned to roots
Rooting distribution over depth	Exponential
Method to calculate evapotranspiration	Priestley–Taylor (1972)
Water dynamics	Capacity approach, multi-soil layer
Model type	Crop specific, dynamic
Simulation time step	Daily

(Source: Kassie et al. (2014)).

Appendix Table 6. Genetic coefficients of maize cultivars calibrated in DSSAT-CSM model

Coefficient	Description	Melkassa-2 (ZM-521)
P1	Thermal time from seedling emergence to the end of the juvenile stage (degree days above the base temperature of 8°C in the juvenile stage)	220.0
P2	Photoperiod sensitivity associated with delayed growth under unfavorable long day length condition (no unit)	0.10
P5	Thermal time from silking to physiological maturity (degree days above the base temperature of 8°C in the maturity stage)	640.0
G2	Potential maximum number of kernels per plant	920.0
G3	Kernel filling rate under optimum condition (mg d^{-1})	7.1
PHINT	Interval in thermal time between successive leaf appearance (degree days above a base temperature of 8°C)	38.9

Source: (Tesfaye et al., 2015)

Appendix Table 7. Experimental information (mean values from 23 Kg ha-1 N and 20 Kg ha-1 P treatment level)

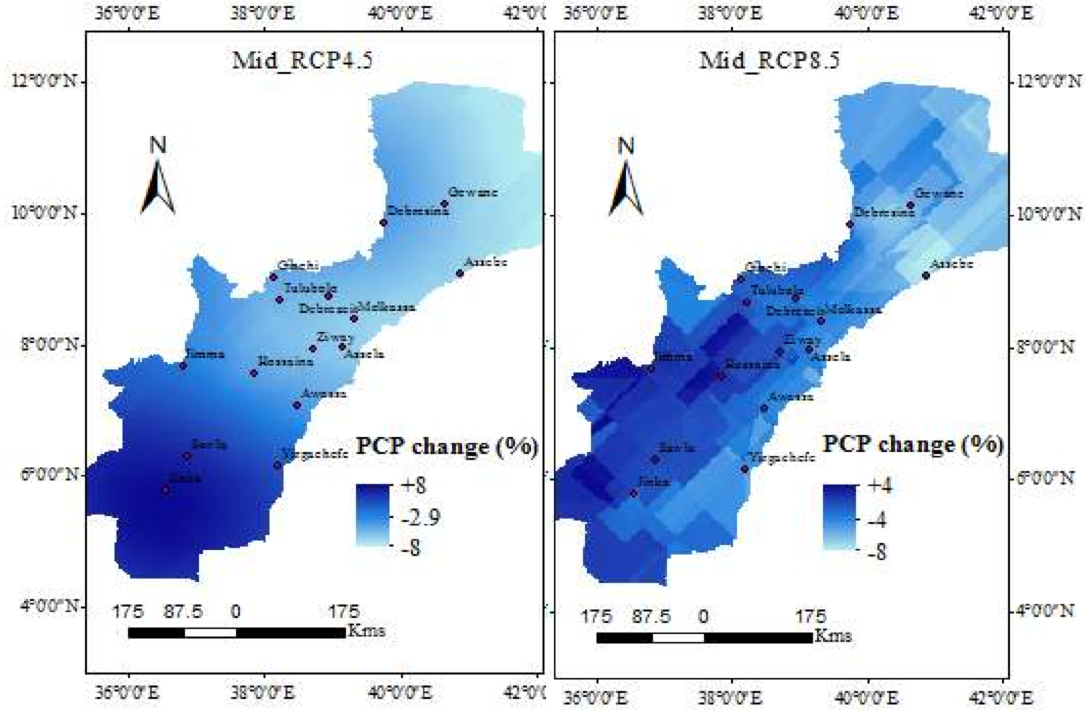
Site	Year	Cultivar	Planting date	Days to emergence	Days to anthesis	Days from planting to maturity	Grain yield (Mg/ ha)	Biomass (ton/ ha)
Melkassa	2010	ZM-521	16 July	7	49	120	4.6	-
	2011		08 July	6	60	150	3.8	8.5
	2012		21 June	7	73	144	3.6	12.5
	2013		08 July	7	66	140	4.4	8.0
	2017		1 July	6	66	128	5.6	18.9
Ziway	2010	ZM-521	25 May	7	49	120	2.8	-
	2011		03 June	8	60	150	2.3	9.1
	2012		13 June	7	73	144	3.9	11.3
	2013		20 June	7	66	140	3.5	10.1
	2015		04 June	7	75	120	3.9/1.3	6.5/3

Appendix Table 8. Projected percent changes in seasonal rainfall (PCP), actual evapotranspiration (ET), mean grain yield (GY) and water productivity (WP) in the mid and far period with respect to baseline period

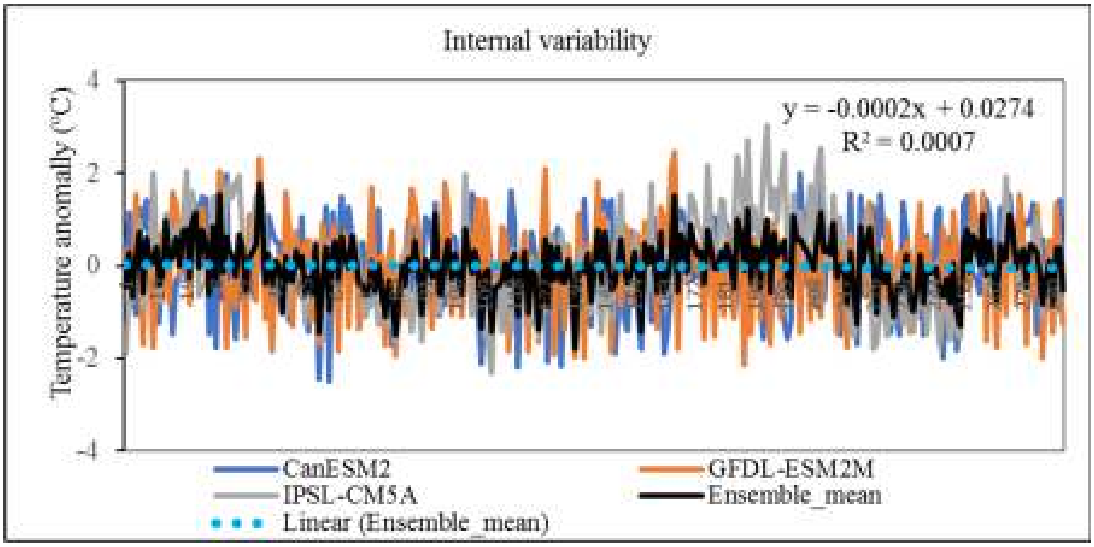
GCM_RCP	Melkassa (Mid)				Melkassa (Far)			
	PCP (%)	ET (%)	GY (%)	WP (%)	PCP (%)	ET (%)	GY (%)	WP (%)
CNRM4.5	-6.6	-7.1	-15	-12	+3.1	-8.2	-8.4	-6.2
CNRM8.5	-4.9	-9.5	-15	-10.8	-11	-14.5	-22.0	-16.0
ECEARTH4.5	-7.5	-7.1	-15	-12.7	-7.2	-2.1	-11.9	-6.8
ECEARTH8.5	-0.2	-8.5	-11.7	-9.5	-4.7	-12.8	-20.2	-16.2
HadGEM2-ES4.5	-15.6	-9.8	-23.3	-13.3	-14.5	-11.9	-20.3	-11.2
HadGEM2-ES8.5	-11	-11.7	-20	-12.5	-20	-16.8	-32.5	-23.2
MPI-ESM4.5	-5.5	-7	-15	-11.7	-7.2	-8.7	-11.9	-6.8
MPI-ESM8.5	-7.7	-10.4	-16.7	-13.6	-17.6	-16.5	-29.7	-21.9
Ensemble mean4.5	-8.5	-7.4	-18.3	-11.0	+0.4	-2.5	-12.7	-8.0
Ensemble mean8.5	-5.8	-9.7	-15	-8.0	-13.7	-15.7	-25.1	-18.5

Appendix Table 9. Projected changes in seasonal rainfall (PCP), actual evapotranspiration (ET), mean grain yield (GY) and water productivity (WP) in the mid and far period with respect to base period at Ziway

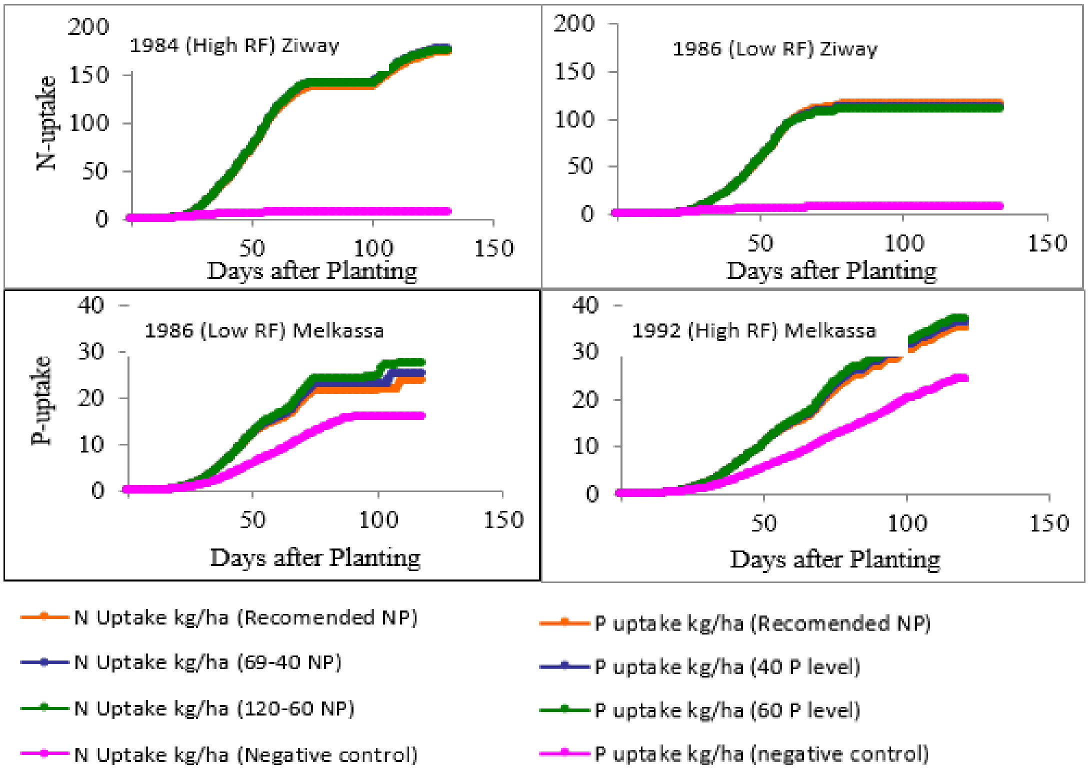
GCM_RCP	Mid period				Far period			
	PCP (%)	ET (%)	GY (%)	WP (%)	PCP (%)	ET (%)	GY (%)	WP (%)
CNRM4.5	-12.4	-8.7	-10.5	0	-0.4	-7.9	0	18.9
CNRM8.5	-11.4	-8.6	-7.9	1.1	-14.7	-12.7	-18.4	-5.6
ECEARTH4.5	-11.1	0.5	-7.9	-1.1	-10.6	-8	-5.3	4.4
ECEARTH8.5	-5.8	-7.1	-5.3	2.2	-17.3	-13.5	-18.4	-5.6
HadGEM2-ES4.5	-11.8	-7.8	-10.5	-5.1	-18.3	-12.3	-13.2	-9.1
HadGEM2-ES8.5	-13.6	-11.1	-13.2	-7.1	-27	-19.5	-31.6	-13.3
MPI-ESM4.5	-10.1	-5.8	-7.9	0	-15.7	-9.8	-7.9	2.2
MPI-ESM8.5	-19.8	-13.6	-13.2	1.1	-31.6	-20.8	-31.6	-13.3
Ensemble mean4.5	-10.1	-5.8	-6.5	0.5	-9.8	-8.6	-5.9	1
Ensemble mean8.5	-15.4	-11.6	-10.5	0.4	-31.6	-20.8	-21.9	-7.4



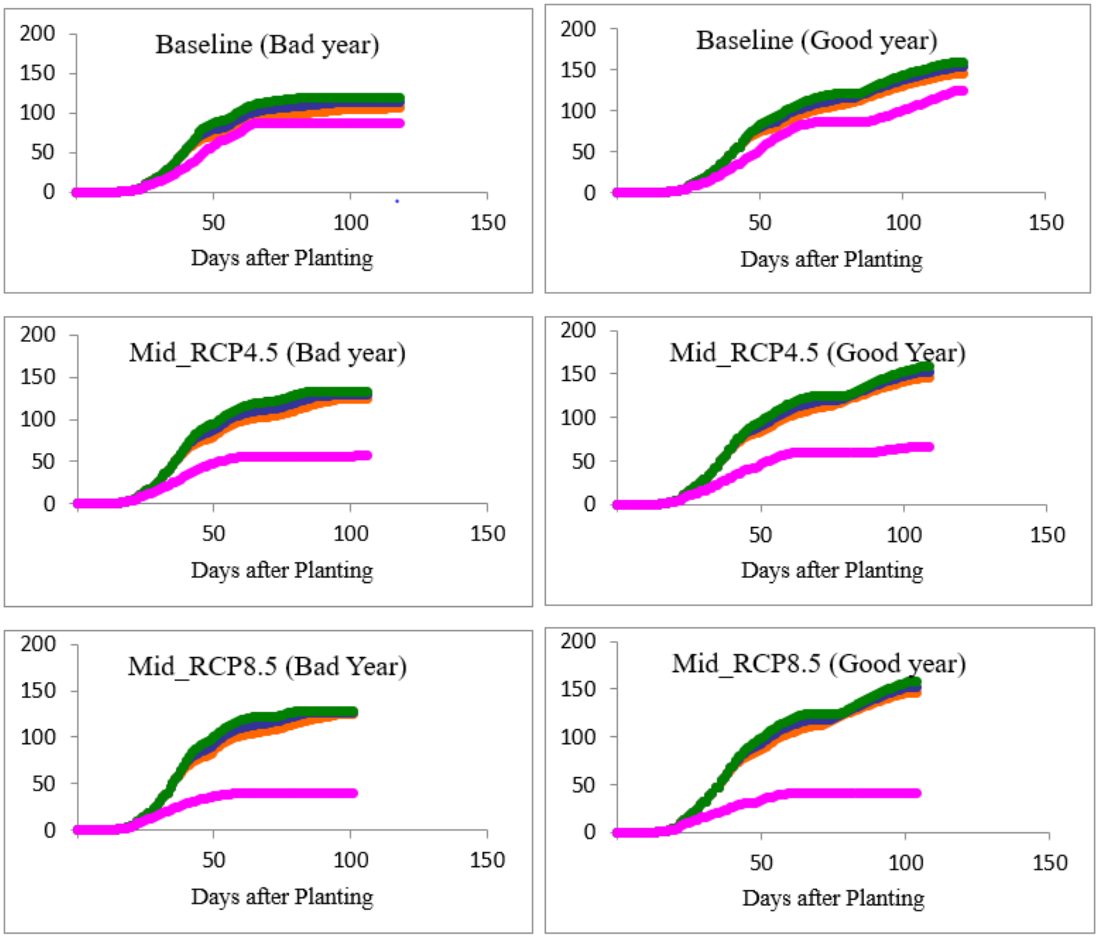
Appendix Figure 1. Projected changes in rainfall as projected by ensemble average of RCA4 based models during mid-century relative to the base period



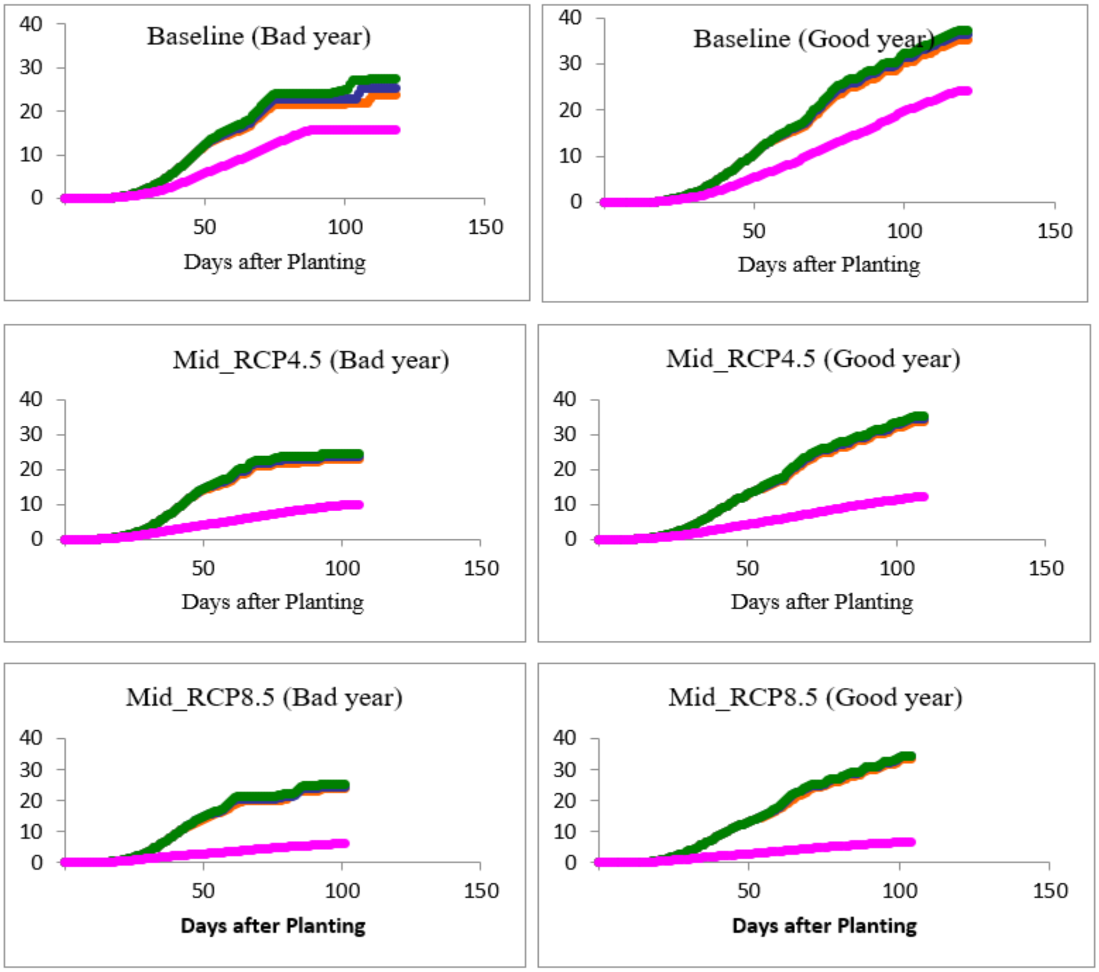
Appendix Figure 2. Internal variability of the climate system simulated by individual models for the GRVB.



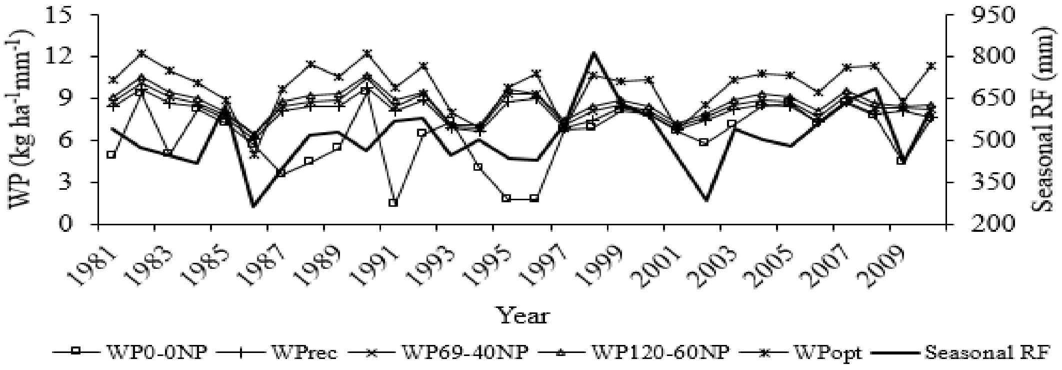
Appendix Figure 3. Seasonal N and P uptake of maize at Melkassa and Ziway during high and low rainfall years simulated by DSSAT crop model.



Appendix Figure 4. Cumulative N uptake under good and bad years during baseline and mid period at Melkassa.



Appendix Figure 5. Cumulative P uptake under good and bad years during baseline and mid period at Melkassa.



Appendix Figure 6. Water productivity simulated by DSSAT cropping system model under different levels of fertilizer rate at Melkassa, CRV of Ethiopia.

Appendix Figure 7. Phosphorous calibration trial (a), NP fertilized vs unfertilized plot (b) and nearby farmers field (c) at Ziway in 2011 main season.

Appendix Figure 8. Pictures taken from field experiment conducted at Melkassa during 2017 main season.

BIOGRAPHICAL SKETCH

The author was born on November 12, 1982 from his father Ademe Mamo and mother Aster Tuji in Illubabor, Oromia. He attended his primary and secondary education at Chora Primary and Junior Secondary School and Dilla Comprehensive Secondary School, respectively. After completing his high school study in 1999, he joined Mekelle University under regular program and graduated with BSc degree in Dryland Crop Sciences in July, 2003. He was then employed by the then Ethiopian Agricultural Research Organization, now Ethiopian Institute of Agricultural Research (EIAR) as Junior Researcher in 2004 based at Melkassa Agricultural Research Centre. In October 2008, he joined Haramaya University and earned his MSc degree in Soil Sciences in 2010. He continued working at EIAR at different positions (from Assistant Researcher-I to Associate Researcher) until he joined Hawassa University in February 2015 to pursue his PhD studies in Soil Sciences.