ASSESSMENT OF THE IMPACTS OF CLIMATE VARIABILITY AND CHANGE ON RAINFED CEREAL CROP PRODUCTIVITY IN CENTRAL TANZANIA

BARNABAS M. MSONGALELI

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2015

EXTENDED ABSTRACT

Though production of cereal crops in Tanzania could succumb to the projected climate change, research has mainly focused on maize (*Zea mays* L), the main staple crop for the country, and just little work has been done to analyse climate change impacts specifically on sorghum [*Sorghum bicolor* (L) Moench]. This study analysed the nature and sources of vulnerability on sorghum production by smallholder farmers due to climate variability and change and evaluated possible farm-level adaptation options that can enhance the adaptive capacity of smallholder farmers in the face of increased climate variability and long-term change in climate. The study was conducted in Dodoma and Singida regions in central Tanzania. Local famers' management practices from databases and surveys were combined with field experimentation and simulation modelling. The Agricultural Production Systems SIMulator (APSIM) and Decision Support System for Agro-technological Transfer (DSSAT) models were calibrated and validated to predict growth and yield of sorghum under rainfed conditions in the case study regions. Three sorghum varieties: *Macia*, *Pato* and *Tegemeo* were used. The models were parameterized using different agronomic parameters (phenological development, dry matter accumulation and grain yield) and climatic data. Efficiency of the models were tested using model validation skill scores including d-stat, root mean square error (RMSE) and regression coefficient (R^2). To understand the nature of vulnerability, long term historical rainfall data were analysed. Simulations were conducted to evaluate the impacts and interactions of adaptation options, namely: staggered planting dates, recommended planting density, and variable fertilizer rates on sorghum and maize yields under long-term climate change towards the mid-century. The long-term rainfall analysis shows that total annual rainfall has so far not changed, but variability in the rainfall distribution within seasons has increased. Experimentation in this study demonstrated that the tested sorghum varieties had variable maturity dates and different responses to prolonged dry spells. Thus, the early maturing variety *Macia* (102 days) was able to avoid terminal drought versus *Pato* (118 days) and *Tegemeo* (114). Statistical analysis show a significant (at 0.05 level) inter-seasonal effect on grain yield and total biomass of the sorghum varieties. Agricultural production systems in semi-arid central Tanzania are projected to be affected by expected changes in climatic conditions over the next decades and century. Simulation results show that Macia will not be affected by climate change. In contrast, early maturing maize variety *Situka* was not able to compensate for the decline in yield under climate change. However, fertilizer application increased *Situka* yield significantly under future climates particularly when early planting was adopted. Coupled with increasing population pressure and declining soil fertility, climate variability and change are relentless driving forces to reduce agricultural productivity in the near future. Because agriculture causes a variety of benefits and challenges, impacts of climate change on agricultural systems are of importance from an economic but also from a social and environmental point of view. Assessment of impacts and potential adaptation supports the decision making processes of farmers, governments, and other stakeholders. Adaptation options such as changes in sowing dates, changes in planting density and fertilizer application were evaluated. To adapt to the changing climate, early sowing and increasing plant density per hectare and fertilizer application would be feasible options. The selection of an earlier sowing date for maize, for instance, would be the appropriate response to offset the negative effect of increased temperature. This change in planting date would allow for the crop to develop during a period of the year with lower

temperatures, thereby decreasing developmental rates and increasing the growth duration, especially the grain filling period. The study also found that site specific agro-ecological conditions such as soil type characterize farmers' responses to decisions on the type of crop and/or crop variety to grow in a given season. This is partly due to their perceptions on soil fertility status among soil types taking spatial variability across the fields into account. Other socio-economic factors ranging from food tastes and preferences to markets and prices, variably but strongly influence decisions on continued adoption of drought tolerant crops (sorghum and millets) versus the susceptible maize. The results show that these factors and associated challenges have the potential to bring negative externalities, therefore, efforts to minimize the impacts from climate variability and change should go alongside with addressing the reported perception and preference challenges. Soil fertility management is therefore likely to be a major entry point for increasing the adaptive capacity of smallholder farmers to climate change and increased climate variability. However, management of other factors related to improved varieties, nutrient resource access and socio-economic factors is critical for rainfed cereal production under changing climate. This dissertation addresses impacts and adaptation to climate change on sorghum production (with some comparison with maize) in the central zone of Tanzania. An overview over different approaches of modelling climate change impacts on crop production as well as a review of studies that analyse climate change impacts on agriculture in sub-Saharan Africa and Tanzania in particular are given in the introductory Chapter 1. Chapter 2 describes the evaluation of the performance of three sorghum varieties at the field level and assessment of their performance over a long-term period using biophysical modelling. In Chapter 3, an approach that integrates the biophysical models

DSSAT and APSIM model with GCMs is used to analyse the impact of climate change on sorghum and maize production. Chapter 4 investigates the influence of driving factors separate from impacts of climate change on the production of sorghum relative to other cereals important in the zone. General discussion and conclusions are given in Chapter 5.

DECLARATION

I, BARNABAS MSOLINI MSONGALELI, do hereby declare to the Senate of Sokoine University of Agriculture that the work that is reported in this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any institution.

__________________________ ______________________

Barnabas Msolini Msongaleli Date

(PhD Candidate)

The above declaration is confirmed by;

__________________________ ______________________

Prof. Filbert B. Rwehumbiza Date

(Supervisor)

__________________________ ______________________

Prof. Siza D. Tumbo Date

(Supervisor)

__________________________ ______________________

Prof. Nganga I. Kihupi Date

(Supervisor)

COPYRIGHT

ACKNOWLEDGEMENTS

I thank the ALMIGHTY GOD for HIS grace, love and strength he offered me to do this work.

This dissertation would not have been possible without assistance from a large number of people. First and foremost, I would like to thank my supervisors, Prof. Filbert Rwehumbiza, Prof. Siza Tumbo and Prof. Nganga Kihupi, for their inspiration, close guidance and advice. I would like to gratefully express my sincere thanks to Elias Letayo and other staff at ARI Hombolo for their support during my field work. I would also like to thank Jans Bobert who introduced me to DSSAT.

I greatly appreciate the scholarship offered to me by the Regional Agricultural Universities Forum for Agricultural Research (RUFORUM). I also thank my employer the University of Dodoma for granting me study leave. I give my vote of thanks to the former Head of Department of Geography Prof. Abiud Kaswamila for his regular follow-up and his words of encouragement.

I appreciate the logistical and material support offered to me by the project "Enhancing Climate Change Adaptation in Agriculture and Water Resources in the Greater Horn of Africa (ECAW)" under the Soil Water Management Research Group (SWMRG) of Sokoine University of Agriculture. I deeply appreciate the training on DSSAT which created a stepping stone for subsequent knowledge in crop modelling. My stay at the Department of Agricultural Engineering and Land Planning at SUA was joyful. Many thanks to my colleagues: Sixbert Mourice, Ndabhemeye Mulengera, Darwin Dodoma, Tolera Abera, Adam Njovu, Shida Lushinge, Ibrahim Kadigi, Jacob Kaingo, Asheri Kalala, Jacob Omollo and Placid Kabalo for their warm friendship and support. I am grateful to all the professors in the department: Prof. Henry Mahoo, Prof. Valerian Silayo, who also provided scientific counsel for this dissertation, for which I am grateful. I am also indebted to others for their assistance and support.

Finally, I would like to thank my wife Bernadeta, sons Bonaventura, Ludovick and Innocent and daughter Gloria for their understanding and moral support during my absence from home for a long period.

DEDICATION

This dissertation is dedicated to the memory of my late father and to my mother Leah Lupandisa. I also dedicate this dissertation to my beloved wife Bernadeta Venance and our children Bonaventura, Gloria, Ludovick and Innocent who endured the pain of separation for the years I was away from home.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS AND ABBREVIATIONS

AfSIS	Africa Soil Information Service
APSIM	Agricultural Production Systems sIMulator
AgMIP	Agricultural Model inter-comparison and Improvement Project
BD	Bulk density
CEC	Cation Exchange Capacity
CERES	Crop Environment Resource Synthesis
CMIP3	Coupled Model Intercomparison Project phase 3
CMIP5	Coupled Model Intercomparison Project phase 5
CV	Coefficient of variation
DAP	Diammonium Phosphate
DSSAT	Decision Support System for Agro-technological Transfer
DUL	Field capacity (Drained Upper Limit)
EP	Early planting
FAO	Food and Agriculture Organization
Finert	Proportion of soil carbon assumed not to decompose
GCMs	Global Circulation Models
GDD	Growing Degree Days
GLAM	General Large Area Model for annual crops
ha	Hectare
ISRIC	International Soil Reference and Information Centre
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
IFPRI	International Food Policy Report Institute
IPCC	Intergovernmental Panel on Climate Change

JFM	January, February, March
LGP	Length of growing period
LL15	Permanent wilting point (Lower Limit at -15 bar pressure)
LP	Late planting
MCWLA	Model to capture the Crop–Weather relation over a Large Area
MNL	Multinomial Logit
N	Nitrogen
NO3-N	Nitrate Nitrogen
NAPA	National Adaptation Programme of Action
NBS	National Bureau of Statistics
P	Phosphorus
PHINT	Phylocron Interval
pH	negative logarithm of soil ion concentration
p	Probability
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RMSE	Root mean square error
SADC	Southern Africa Development Programme
SAT	Volumetric water content at saturation
SOC	Soil organic carbon
SOILWAT	Soil water module in APSIM
SMIP	Sorghum and Millet Improvement Programme
SRES	Special Report on Emissions Scenarios
SSA	Sub Saharan Africa

TNPS	Tanzania National Panel Survey
URT	United Republic of Tanzania
WISE	World Inventory of Soil Emission Potentials

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Vulnerability of cereal production systems to climate change

Vulnerability to climate change is how susceptible people are to harmful stresses and their ability to respond or adapt to these stresses (Adger, 2006). Sub-Saharan Africa's (SSA) population is estimated at almost 2 billion people by 2050 (UNDP, 2012). Meeting the increasing demand for food is jolted by stresses put on agricultural production by climate change among other factors under current agricultural practices. Thus, sharp and sustainable increases in cereal crop yields are required over the next twenty to thirty years to enhance food security, incomes and livelihoods to keep pace with these developments. A large fraction of Africa's smallholder crop production depends directly on rainfall. For example, studies have reported that 89% of cereal production in SSA is under rainfed agriculture (Cooper *et al*., 2008; Rosegrant *et al*., 2002). Rainfed cereal production is also a major component of farming systems in East Africa. The majority of Tanzanians depend largely on rainfed agriculture which employs about 75% of the population (URT, 2013).

Major cereals in Tanzania include maize, rice, wheat and sorghum. Climate change presents an obvious threat to the country's cereal production systems, which translates into production risks, due to the increase in probability of extreme events, the uncertainty of the timing of field operations and lack of investments in new agricultural technologies. An analysis of projected climate change impacts on agricultural productivity is essential in order to elucidate the concern for food security in the present and future periods and ensuring that the implications of the impacts are communicated to public and policy makers (IFPRI, 2009, IPCC 2007).

Productivity of cereals in Tanzania is increasingly threatened by several factors including land resource deterioration, declining soil fertility, increasing drought frequency, declining fertilizer consumption and increasing variability in rainfall (Malley *et al*., 2009). When these are coupled with the projected increase in population, the current cereal crop yields and productivity trends will need to increase by at least 70% to meet demands by 2050 (Alexandratos and Bruinsma, 2012).

In-depth analysis of these factors is vital for sustainable increase in cereal crop yields required over the next twenty to thirty years to enhance food security, incomes and livelihoods. While studies on adaptation and coping with climate variability and change have become key themes in global climate discussions and policy initiatives, there is a dearth of literature on studies specifically on the impacts on sorghum productivity in the semi-arid areas of Tanzania. Given that maize has gradually replaced sorghum and millet as staple food in semi-arid areas of Tanzania, the trend has dictated several studies on vulnerability to climate variability and change to focus on maize, but implications for the drought tolerant crops (sorghum and millet) prevalent in the semi-arid areas remain uncertain.

Several studies identify regions sensitive to progressive climate change (Lobell *et al*., 2008; IPCC, 2007; Jones and Thornton, 2003), eastern Africa being one of them, but scientific knowledge remain sparse and fragmented as to how current cereal farming systems evolve at local scale. For Tanzania, while it is estimated that yields from rainfed agriculture can be reduced by up to 50% by 2020 (IPCC, 2007), only few studies have quantitatively concurred or refuted the estimates (URT, 2007). Previous modelling studies dealing with the assessment of the impacts of climate change in Africa, though very useful at the continental or regional scale, provided little information to guide decision makers at country or district level on the precise extent of the impacts of climate change (Baethgen, 2010; IFPRI, 2009; Thornton *et al*. 2009). For instance the projected decline in cereal production in SSA by a net 3.2 percent by 2050 and the overall increase in millet and sorghum yields as a result of climate change (IFPRI, 2009) gives rather conflicting information about the exact locations where such decline or increase will occur.

In that regard, investigations at various scales are needed to elucidate the crop yield projections. Moreover, the low level of human development, extreme poverty and high dependence on rainfed agriculture makes Tanzania more vulnerable to projected climate change, making adaptation a great necessity. The Tanzania National Adaptation Programme of Action (NAPA) (URT, 2007) are apprehensive about previously highly productive areas such as the southern highlands being under threat due to declining rainfall amount and increased spatial and temporal rainfall variability.

Agricultural adaptation is defined as the adjustment in agricultural systems in response to actual or expected climatic stimuli or their effects, to moderate harm or exploit beneficial opportunities (IPCC, 2001). Thus agricultural adaptation is a key element in climate change policy that warrants an in-depth study. The scope of the current study is limited to farm level adaptations consisting of adjustments and/or changes in crop agronomic practices undertaken by farmers. In a situation where most of the agricultural crop production is rain-fed, farm level adaptations are crucial for enhancing capacity to reduce food insecurity. These can be placed into two groups: ex ante measures, for which action is taken in anticipation of a given climate realization and ex post responses, which are undertaken after the event is realized (Burke and Lobell, 2010). According to Pandey *et al*. (2007) cited in Burke and Lobell, (2010), ex ante adaptations to climate variability often centre around strategies of diversification, which attempt to capitalize on the differential effects that a given climate event might have on different crops and activities in a given year. Examples include, diversifying the location of farm plots to take advantage of high spatial variability of rainfall, grow a range of crops or crop varieties with different sensitivities to climate, or to diversify income sources into non-farm enterprises that are less sensitive to climate (Pandey *et al*., 2007). At policy level, adaptation strategies may include investment in the development of drought and heat tolerant crops, and also through examining how to empower and encourage farmer adaptation to climate change at a range of spatial scales (Morton, 2007).

Crop simulation models (CSMs) can provide good simulations of crop productivity under the impact of variable weather in a range of soil, water and crop management choices (Cooper *et al*., 2008). Whitbread *et al*. (2010), Gregory and Ingram (2008) and Mathews *et al.* (2002) give an overview of different models and their components across tropical agricultural systems. However, for CSMs to have plausible applications in studies on impacts and adaptation options in local environments, appropriate and representative information on crops including crop variety is a vital requirement (Craufurd *et al.,* 2013).

The threat that climate variability poses to rain-fed agriculture necessitates the understanding of its potential impacts at various scales in order to reduce the vulnerability and thereby secure the livelihoods of the smallholder farmers (Sivakumar *et al*., 2005; Lansigan, 2003; Chipanshi *et al.,* 2003). Studies have established that temperature and rainfall are the most critical variables for crop productivity (Chen *et al*., 2013; Lobell *et al*., 2011; Gornall *et al*., 2010; Lobell and Burke, 2008; Tilahun, 2006). Evidence points to the fact that, in the semi-arid regions of Africa where agricultural systems rely on rainfall as a sole source of moisture for crop production, seasonal rainfall variability leads to highly variable production levels and risks (Cooper *et al*., 2008).

Since agricultural practices are climate-dependent and crop yields vary from year to year depending on climate variability, rainfed agriculture is particularly exposed to changes in climate. Laux *et al*. (2010) observe that high spatial and temporal variability of rainfall, reflected by dry spells and recurrent droughts and floods are considered to be the most important factors affecting agricultural productivity in SSA. Elsewhere, comparable negative relationships between climate variability and sorghum yields were reported by Prasad *et al*. (2006); Prasad *et al*. (2008) and

Prasad and Staggenborg (2009). Prasad *et al*. (2008) indicate that maximum decreases in yield of grain sorghum occur when high temperature stress is imposed at flowering and 10 days before flowering.

For Tanzania in particular, an empirical study (Rowhani *et al*., 2011) on the impacts of climate variability on maize, sorghum and rice yields, focused on intra- and inter-seasonal temperature and rainfall variability and concluded that increased rainfall variability during the growing season was responsible for reduction of the crop yields. It is, however, worth noting that, Tanzanian climate is influenced by large-scale climatic events such as the El Nino-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Giannini, 2008) and therefore climate variability associated with these two phenomena significantly contribute towards the variability in crop yields in Tanzania. Against this background, the present study aimed at highlighting how important it is to address and understand impacts of climate variability in reducing the vulnerability of dryland farmers.

1.2 Climate Change Impact Assessment

Climate change projections lead to uncertainty due to the use of multiple models, databases, different levels of aggregation and different number of scenarios (Liu *et al*., 2013; Challinor *et al*., 2009). Methods are, therefore, required to reduce the uncertainty and thus improve the estimates of the impacts of climate variability and change on agriculture. However, most crop models are designed to run at the field scale, which may not be appropriate for policy decisions. Therefore, large-area modelling is required to reduce the uncertainty due to future climate projections, establish food security warning systems, predict food production in future and examine the options for adaptations (Tao *et al.,* 2009). Berg *et al*. (2013) observe that more reliable agricultural impact assessments over tropical regions can be provided if the uncertainty in rainfall projections over dry areas is narrowed through reducing the uncertainty in aggregated impacts. They contend that in dryland areas larger yield changes occur that are driven by rainfall changes which encompass more uncertainty. Considering sorghum, some studies have indicated high risks to rainfed sorghum production posed by climate change (MacCarthy and Vlek, 2012; Srivastava *et al*., 2010). Results indicate the vulnerability, particularly of the smallholder (low input) farmers to climate change impacts, thus necessitating inclusion of an integrated approach to reduce the impact and give desirable results for sustaining the sorghum yields. Options such as high temperature tolerant varieties and soil moisture conservation have shown high potential as additional options to be considered for climate change adaptation (Hellin *et al*., 2012).

Despite the variability in the methods and models used in the assessments, and the emission scenarios simulated, there is an agreement that maize yields in SSA may be reduced overall by 10-30% to the middle of the century (Lobell *et al*., 2008; Challinor *et al*., 2007). Research has focused on assessments of the potential impacts of climate change on agriculture at different scales. For example, national, regional and global estimates of potential climate change on agricultural production have been conducted using statistical models (Rowhani *et al*., 2011; Lobell and Burke, 2010; Lobell *et al*., 2008), process- based crop simulation models (Tumbo *et al*., 2012; Thornton *et al*., 2009; Parry *et al*. 2004; Alexandrov and Hoogenboom, 2000; Mwandosya *et al*., 1998) and a combination of biophysical and economic simulation models (IFPRI, 2009; Challinor *et al*., 2010; Arndt *et al.,* 2011; Moriondo *et al*., 2011; Rosenzweig *et al*., 2013).

Common methods in climate change impact assessment over large areas have evolved, specifically crop–climate modelling with a focus on crop phenology and yield. Downing *et al.* (2002) reviewed the methods including a site within a polygon, grids with relational data on polygons, spatially uniform grids, interpolation and stochastic spatial models and concluded that no one methodology was the best. Priya and Shibasaki (2001) developed a "Spatial EPIC" model to simulate crop yield in India on a pixel–by–pixel basis following a row and column sequence with multiple soil, climate, and management information provided in the form of geographic information system (GIS) layers. Other studies utilized methods such as crop model scaling approaches (Hansen and Jones, 2000) and the yield correction approach (Jagtap and Jones, 2002).

Owing to the need to aggregate input parameters of a crop model due to the heterogeneity of the larger region, Hansen and Jones (2000) proposed the development of simpler crop models designed specifically to work at the larger spatial scale. On the other hand, Challinor *et al*. (2009) expound on the need to simulate the impacts of climate variability and change on crops in a process-based fashion using the output from climate models directly (i.e. without any downscaling). On the other hand, grids have been used in several studies (Ventrella *et al*., 2012; Wang *et al*., 2011; IFPRI, 2009). As climate change projections form the basis for assessing the impact on crop production and developing adaptation strategies, reliable future changes with reduced level of uncertainty are very important. In that regard, IPCC (2007) for example, suggest the use of regional climate models (RCM) run at high resolution of 25 km × 25 km grid could predict the future climate with high confidence.

Use of simplified crop models to simulate crop growth and development over larger areas has been demonstrated through GLAM (Challinor *et al*., 2004) and MCWLA (Tao *et al*., 2009). GLAM was successfully used to simulate groundnut yield over large areas in India (Challinor *et al*., 2004) and to study crop-atmosphere feedbacks across the tropics (Osborne *et al*., 2007). Experiences of DSSAT (a field scale model) application at spatial scale are reported by Batchelor *et al*. (2002), Wang *et al*. (2011) and Geethalakshmi *et al*. (2011). Wang *et al.* (2011) demonstrate a spatial application of DSSAT (CERES-Maize) to simulate the effects of climate change on maize yield, on a grid by grid scale, rather than following the common representative site approach. They observed that depending on data availability, such a method provides a potentially more accurate simulation for each grid cell. Hence, the model can be easily extended to any annual crop for the investigation of the impacts of climate variability (or change) on crop yield over large areas. Statistical or empirical models though lacking the capability to mechanistically capture the effects of weather variability on crop growth, is another approach in the assessment of impacts of climate change. Despite their deficiencies, Lobell and Burke (2010) and Lobell *et al*. (2011) reiterate the use of statistical models as one of the methodologies for assessing the biophysical effects of climate on crop yield.

1.3 Justification

Climate variability and projected future climate change will have increasingly negative impacts on Tanzanian crop production systems (and, consequently, on food security and rural livelihoods), and will exceed the limits to adaptation in the most vulnerable agricultural regions. IPCC (2007) estimates that in Tanzania, yields from rainfed agriculture can be reduced by up to 50% by 2020. The estimates appear highly elevated and exacerbate concerns about food security considering the projection period being in the near-future. Thus predicting impacts on crop yield under different climate change scenarios is needed to further quantify the uncertainty in crop yield. Mwandosya *et al*. (1998) used CERES-Maize to simulate yields of maize under the baseline (1951 -1980) and changed climate scenario (2xCO_2) from the UK89 model expected by the year 2100. Results show that in semi-arid areas of Tabora and Dodoma increasing temperature and decreasing rainfall are estimated to reduce maize yields by between 80% and 90%. Moreover, Arndt *et al*. (2011) conclude that food security in Tanzania appears likely to deteriorate as a consequence of climate change through reductions in food production, due to increases in temperature and changes in rainfall patterns. However, Mwandosya *et al*. (1998) did not account for the spatial variability in soils and crop cultivars.

Proper usage of climate projections for agricultural impact assessment is of paramount importance in order to properly inform adaptation. Modelling approaches have shown great potential for ensuring sustainable agriculture over a wide range of climates around the world and crop growth models have become state-of-the-art research tools and an important component of agriculture-related decision-support systems (Murthy, 2004; Stephens and Middleton, 2002). Since sorghum is grown as a rainfed crop, the climatic factors play a significant role in its productivity. IPCC (2007) recommends further exploration of the potential of sorghum to contribute to food security needs, particularly in the light of climate variability and change that is expected to lead to higher temperatures, more variable rainfall and extreme weather events, and thus negatively affecting agricultural production. In coping with rainfall variability, smallholder farmers diversify cropping by mainly planting resistant crops such as sorghum, millet, green grams and cowpeas. However, these tactical strategies lack quantification of their responses in respect of benefits or disadvantages. Reports are already emerging of smallholder farmers in the southern highlands of Tanzania not being sure of when to sow their maize (Malley *et al*., 2009). The shifts and unpredictability of maize planting dates are a clear manifestation of the increasing impacts of climate variability on cropping systems. Research in agriculture, food security and climate change is therefore, highly desirable in order to improve understanding of uncertainty and to allow more confident decision-making on resource allocation.

This study adopts a simulation framework which takes into account the spatial variability in soils, varieties, sowing dates and crop management and their effects on crop productivity. Sorghum and maize yield responses to current and future climate scenarios were simulated using crop simulation models. A methodology based on Rosenzweig *et al*. (2013) was adapted for this study. The methodology allows use of spatially aggregated climate (daily weather), soils, land use and farm level management data to minimize the uncertainty.

1.4 OBJECTIVES

1.4.1 Overall objective

To assess the impacts of current variability and future changes in climate on productivity of rainfed sorghum in central Tanzania.

1.4.2 Specific objectives

i) To parameterize and evaluate APSIM to simulate growth, development and yield of sorghum varieties.

ii) To simulate and compare yields of sorghum and maize under baseline and future climatic conditions and evaluate uncertainty of impacts and adaptation options.

iii) To determine the extent of evolution of the dynamics and trends in sorghum production systems.

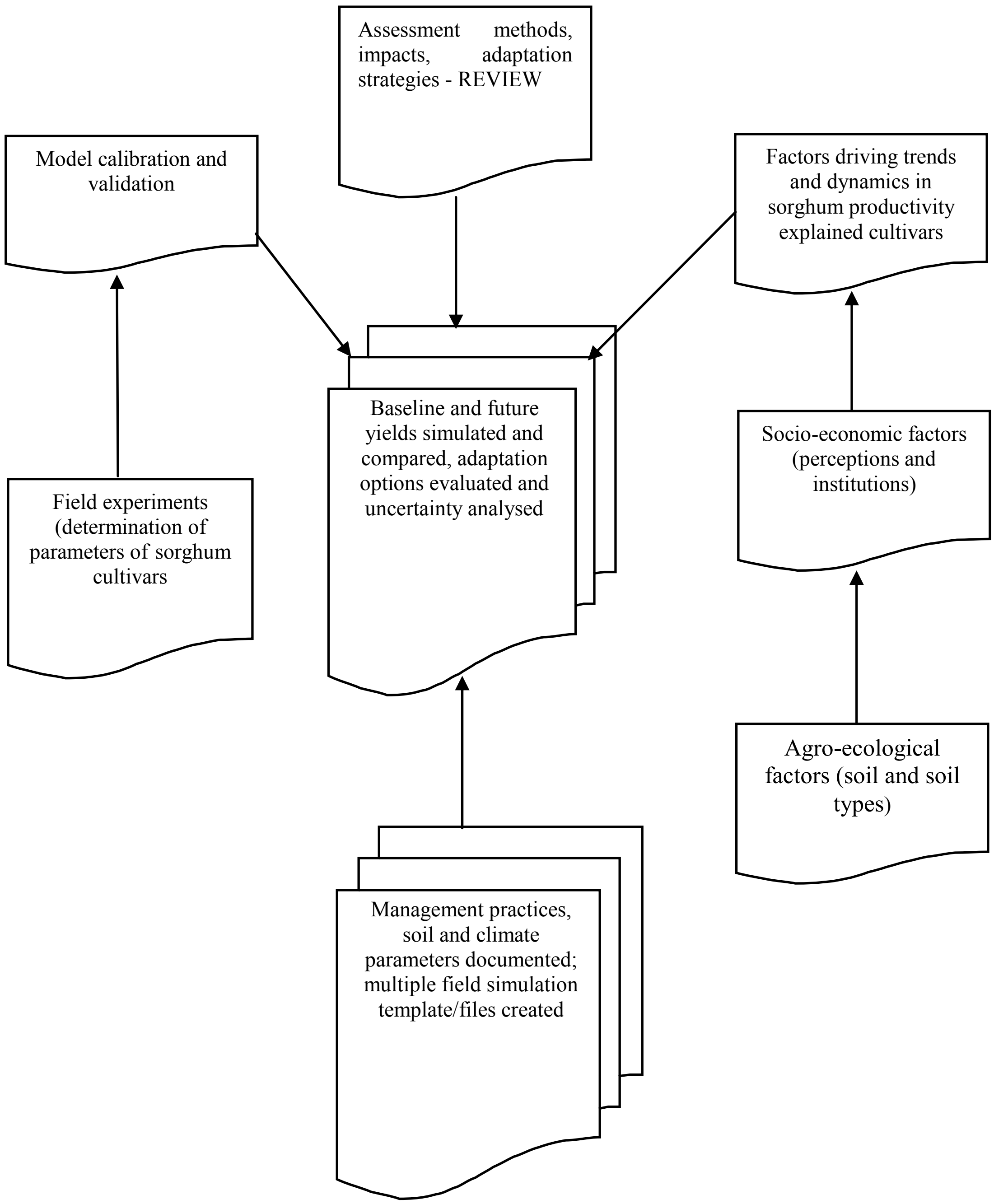


Figure 1.1: Conceptual framework

1.5 REFERENCES

Adger, W. N. (2006). Vulnerability. *Global Environmental Change* 16: 268 – 281.

Alexandratos, N. and Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO. 146pp.

Alexandrov, V. A. and G. Hoogenboom. (2000). The impact of climate variability and change on crop yield in Bulgaria. *Agricultural and Forest Meteorology* 104: 315 – 327.

Arndt, C., Farmer, W., Strzepek, K. and Thurlow, J. (2011). Climate change, agriculture and food security in Tanzania. Working Paper No. 2011/52 United Nations University-World Institute for Economic Development Research (UNU-WIDER), 26 pp.

Baethgen, W. E. (2010). Climate risk management for adaptation to climate variability and change. *Crop Science* 50: 70 - 76.

Batchelor, W.D., Basso, B., Paz, J.O., 2002. Examples of strategies to analyse spatial and temporal yield variability using crop models. *European Journal of Agronomy* 18 (1–2): 141 – 158.

Berg, A., de Noblet-Ducoudr´e, N., Sultan, B., Lengaigne, N. and Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology* 170: 89 - 102.

Burke, M. and Lobell, D. (2010). Food Security and Adaptation to Climate Change: What Do We Know? *In: Climate Change and Food Security: Adapting Agriculture to a Warmer World. (Edited by Lobell, D. and Burke, M.)*, Springer, Netherlands. pp. 133 – 153.

Challinor, A. J., Ewert, F., Arnold, S., Simelton, E. and Fraser, E. (2009). Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany* 60: 2775 - 2789.

Challinor, A. J., Wheeler, T. R., Slingo, J. M., Craufurd, P. Q. and Grimes, D. I. F. (2004). Design and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology* 124: 99 - 120.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P. and Kassam, A. (2007). Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change* 83: 381 - 399.

Challinor, A. J., Simelton, E. S., Fraser, E. D. G., Hemming, D. and Collins, M. (2010). Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. *Environmental Research Letters* 5(3): 034012, 8pp.

Chen, C., Baethgen, W. E. and Robertson, A. (2013). Contributions of individual variation in temperature, solar radiation and precipitation to crop yield in the North China Plain, 1961–2003. *Climatic Change* 116: 767 -788.

Chipanshi, A. C., Chanda, R. and Totolo, O. (2003). Vulnerability assessment of the maize and sorghum crops to climate change in Botswana. *Climatic Change* 61: 339 - 360.

Cooper, P. J. M., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B. and Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture Ecosystems and Environment* 126: 24 - 35.

Craufurd, P. Q., Vadez, V., Krishna Jagadish, S.V., Vara Prasad, P.V., Zaman-Allah, M. (2013). Crop science experiments designed to inform crop modeling**.** *Agricultural and Forest Meteorology 170: 8 – 18.*

Downing, T. E., Butterfield, R. E., Bindi, M., Brooks, R. J., Carter, T. R., Del_Eecolle, R., Harnos, Z. S., Harrison, P. A., Iglesias, A., New, M., Moss, S., Olesen, J. E., Orr, J. L., Porter, J., Semenov, M. A. and Wolf, J. (2002). Scaling methods in regional integrated assessments: from points upward and from global models downwards. *Integrated Assessment* 3: 167 – 187.

Geethalakshmi, V., Lakshmanan, A., Rajalakshmi, D., Jagannathan, R. Sridhar, G., Ramaraj, A. P., Bhuvaneswari, K., Gurusamy, L. and Anbhazhagan, R. (2011). Climate change impact assessment and adaptation strategies to sustain rice production in Cauvery basin of Tamil Nadu. *Current Science* 101: 342 - 347.

Giannini, A., Biasutti, M., Held, I. M. and Sobel, A. H. (2008). A global perspective on African climate. *Climate Change* 90: 359 – 383.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. and Wiltshire, A. (2010). Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society of London*. Series B, Biological sciences 365(1554): 2973 – 2989.

Gregory, P. J. and Ingram, J. S. I. (2008). Climate change and the current "food crisis". *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources,* 3, No. 099. 10pp.

Hansen, J. W. and Jones, J. W. (2000). Scaling-up crop models for climatic variability applications. *Agricultural Systems* 65: 43 - 72.

Hellin, J., Shiferaw, B., Cairns, J. E., Reynolds, M., Ortiz-Monasterio, I., Banziger, M., Sonder, K. and La Rovere, R. (2012). Climate change and food security in the developing world: Potential of maize and wheat research to expand options for adaptation and mitigation. *Journal of Development and Agricultural Economics* 4: 311 - 321.

International Food Policy Research Institute (IFPRI) (2009). *Climate Change Impact on Agriculture and Cost of Adaptation. Food Policy Report*. IFPRI, Washington DC. 30pp.

IPCC, (2001). Climate change: Impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 761pp.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. (Edited by Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. and Hanson, C. E.)* Cambridge University Press, Cambridge. 976pp.

Jagtap, S. S. and Jones, J. W. (2002). Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. *Agriculture Ecosystem and Environment* 93: 73 – 85.

Jones, P. G. and Thornton, P. K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change* 13: 51 – 59.

Lansigan, F. P. (2003). Assessing the impacts of climate variability on crop production, and developing coping strategies in rainfed agriculture. UN CGPRT Monograph No. 43, Bogor, Indonesia, 36pp.

Laux, P., Jäckel, G., Tingem, R. M. and Kunstmann, H. (2010). Impact of climate change on agricultural productivity under rainfed conditions in Cameroon - A method to improve attainable crop yields by planting date adaptations. *Agricultural and Forest Meteorology* 150: 1258 - 1271.

Liu, J., Folberth, C., Yang, H., Rockstrom, J., Abbaspour, K. and Zehnder, A. J. B. (2013). A global and spatially explicit assessment of climate change impacts on crop production and consumptive water use. PLoS ONE 8(2): 57750. 13pp.

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P. and Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science* 319: 607 - 610.

Lobell, D. B., Bänziger, M., Magorokosho, C. and Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change* 1: 42 - 45.

Lobell, D. B. and Burke, M. B. (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters* 3: 034007, 8 pp.

MacCarthy, D. S. and Vlek, P. L. G. (2012). Impact of climate change on sorghum production under different nutrient and crop residue management in semi-arid region of Ghana: A modelling perspective. *African Crop Science Journal* 20: 243 - 259.

Malley, Z. J. U., Taeb, M. and Matsumoto, T. (2009). Agricultural productivity and environmental insecurity in the Usangu plain, Tanzania: policy implications for sustainability of agriculture. *Environment, Development and Sustainability* 11: 175 - 195.

Mathews, R., Stephens, W., Hess, T., Middleton, T. and Graves, A. (2002). Applications of crop/soil simulation models in tropical agricultural systems. *Advances in Agronomy*. 76: 31 - 124

Moriondo, M., Giannakopoulos, C. and Bindi, M. (2011). Climate change impact assessment: the role of climate extremes in crop yield simulation. *Climatic Change* 104: 679 – 701.

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proceeding of National Academy of Science* 104 (50):19680 - 19685.

Murthy, V. R. K. (2004). Crop growth modelling and its applications in agricultural meteorology. *In*: *Proceedings of the Training Workshop on Satellite Remote Sensing and GIS Applications in Agricultural Meteorology*. (Edited by Sivakumar, M. V. K. *et al*.), 7 – 11 July 2004, Dehra Dun, India. 235 - 261 pp.

Mwandosya, M. J., Nyenzi, B. S. and Luhanga, M. L. (1998). The Assessment of Vulnerability and Adaptation to Climate Change Impacts in Tanzania. Dar-es-Salaam, Tanzania: Centre for Energy, Environ. Sci. Technol. CEEST). 159pp.

Osborne, T. M., Lawrence, D. M., Challinor, A. J., Slingo, J. M. and Wheeler, T. R. (2007). Development and assessment of a coupled crop-climate model. *Global Change Biology* 13: 169 – 183.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14: 53 – 67.

Prasad, P. V. V. and Staggenborg, S. A. (2009). Growth and production of sorghum and millets. In soils, plant growth and crop production –Volume II. *In*: Encyclopaedia of life Support Systems, Eolss Publishers, Oxford, UK. [http:// www.eolss.net]. Site visited on 17/8/2012.

Prasad, P. V. V., Boote, K. J. and Allen, L. H. (2006). Adverse high temperature effects on pollen viability, seed set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperature. *Agricultural and Forest Meteorology* 139: 237 - 251.

Prasad, P. V. V., Pisipati, S. R., Mutava, R. N. and Tuinstra, M. R. (2008). Sensitivity of Grain Sorghum to High Temperature Stress during Reproductive Development. *Crop Science*. 48: 1911 - 1917.

Priya, S. and Shibasaki, R. (2001). National spatial crop yield simulation using GIS–based crop production model. *Ecological Modelling* 136(2–3): 113 – 129.

Rosegrant, M. W., Cai, X., Cline, S. and Nakagawa, N. (2002). The role of rainfed agriculture in the future of global food production. Discussion paper 90, International Food Policy Research Institute, Environment and production technology division, Washington, DC. 106pp.

Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G. and Winter, J. M. (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP). Protocols and pilot studies. *Agricultural and Forest Meteorology* 170: 166 - 182.

Rowhani, P., Lobell, D. B., Linderman, M. and Ramankutty, N. (2011). Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology* 151: 449 – 460.

Sivakumar, M. V. K., Das, H. P. and Brunini, O. (2005). Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. *Climatic Change* 70: 31 - 72.

Srivastava, A., Naresh Kumar, S. and Aggarwal, P. K. (2010). Assessment on vulnerability of sorghum to climate change in India. *Agriculture Ecosystems and Environment* 138: 160 -169.

Stephens, W. and Middleton, T. (2002). Why has the uptake of decision support systems been so poor? In: *Crop-soil simulation models*. (Edited by Matthews, R. and Stephens W.), CAB International, Wallingford. pp. 129 - 147.

Tao, F., Yokozawa, M. and Zhang, Z. (2009). Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization and uncertainties analysis. *Agricultural and Forest Meteorology* 149: 831 - 850.

Thornton, P. K., Jones, P. G., Alagarswamy, A. and Andresen, J. (2009). Spatial variation of crop yield responses to climate change in East Africa. *Global Environmental Change* 19: 54 - 65.

Tilahun, K. (2006). Analysis of rainfall climate and evapotranspiration in arid and semi-arid regions of Ethiopia using data over the last half a century. *Journal of Arid Environments* 64: 74 - 487.

Tumbo, S. D., Kahimba, F. C., Mbilinyi, B. P., Rwehumbiza, F. B., Mahoo, H. F., Mbungu, W. B. and Enfors, E. (2012). Impact of projected climate change on agricultural production in semi-arid areas of Tanzania: A case of Same district. *African Crop Science Journal*. 20 (2): 453 – 463.

UNDP (2012). Africa Human Development Report 2012. Towards a Food Secure Future. [http://www.afhdr.org]. Site visited on 22/5/ 2013.

URT (2007) United Republic of Tanzania, "National Adaptation Programme of Action (NAPA)" Division of Environment, Vice President's Office, Dar es Salaam. 61pp.

URT. (2013). *Tanzanian Agricultural Budget Report for the year 2012/2013*. Dar-es-Salaam: Tanzania Government Printer. 76pp.

Ventrella, D., Charfeddine, M., Giglio, L. and Castellini, M. (2012). Application of DSSAT models for an agronomic adaptation strategy under climate change in Southern Italy: optimum sowing and transplanting time for winter durum wheat and tomato. *Italian Journal of Agronomy* 7: 16 - 28.

Wang, M., Li, Y., Ye, W., Bornman, J. F. and Yan, X. (2011). Effects of climate change on maize production and potential adaptation measures: a case study in Jilin Province China. *Climate Research* 46: 223 – 242.

Whitbread, A. M., Robertson, M. J. Carberry, P. S. and Dimes, J. P. (2010). How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa, *European Journal of Agronomy* 32: 51 – 58.

CHAPTER TWO

2.0 PERFORMANCE OF SORGHUM VARIETIES UNDER VARIABLE RAINFALL IN CENTRAL TANZANIA

ABSTRACT

Performance of improved sorghum varieties under the realm of rainfall variability across central Tanzania was investigated. The study has enabled the determination of crop parameters of dominant sorghum cultivars and parameterization of Agricultural Production Systems sIMulator (APSIM) for subsequent simulations to understand the response of sorghum to variable rainfall under semi-arid conditions. Three adapted sorghum varieties were planted in randomized complete blocks replicated three times. The calibrated and validated APSIM was used to simulate long term production trends of grain yield based on the weather conditions in central Tanzania. Analyses of historical (1961-2010) rainfall indicate a mix of non-significant and significant trends in the onset, cessation and length of the growing season across stations in central Tanzania. A 30 year simulated sorghum yield series analysed based on seasonal rainfall distribution indicate the concurrence of lower grain yields with the 10-day dry spells in the first or second decade of March during the growing season the stage coinciding with the period from flag leaf stage to start of grain filling. Moreover, temporal correlations between simulated grain yields at different locations and seasonal total rainfall show that approximately 30% of variability in yields is explained by rainfall. This spatial and temporal variability in simulated sorghum grain yields implies that small-holder farmers must take into consideration the challenges imposed by moisture stress during the cropping season assuming the

soil fertility factor is kept constant. The results signify the impacts of rainfall variability on cropping system of semi-arid conditions, thus the need for designing appropriate agronomic and water management strategies to offset the negative influence in the study area and elsewhere.

Keywords: sorghum, phenological parameters, semi-arid, rainfall variability, crop simulation modelling

2.1 INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is an important and widely adapted small-grain cereal grown in the tropics and subtropics and a staple food grain in food-insecure regions of Asia, Africa and Central America (Craufurd *et al*., 1999; Murty *et al*., 2007). Sorghum ranks fifth globally in terms of production and acreage, estimated at 56.59 million metric tons produced on about 45 million hectares (FAOSTAT, 2012). Sorghum ranks second in importance after maize in Africa with a mean yield of 0.8 t/ha from a cultivated area of about 24 million hectares (Maredia *et al*., 2000). According to a recent review by Keya and Rubaihayo (2013) sorghum ranks fifth after maize, cassava, rice and wheat as staple in Tanzania. Nonetheless, sorghum plays a significant role in fighting hunger and food insecurity in the central high plateau comprising Singida and Dodoma regions of Tanzania owing to its drought-tolerance.

The initiatives to promote sorghum production are mostly a government strategy to enable the country meet household food security needs (Monyo *et al*., 2004) but also increase rural income especially now that new markets are emerging (Makindara *et al*., 2013). The area under sorghum production has been increasing from 736 200 ha in 2000 to 811 164 ha in 2011 but the national average yield per hectare has only slightly increased from 0.8 tons per hectare in 2000 to 1.0 tons per hectare in 2011 (FAOSTAT, 2012). Despite the great potential shown for growth and expansion of the crop, promotion efforts are rundown by higher gaps and variability in production from the expected potential yields and the actual yields. The expected potential yield for the Macia sorghum variety, for instance, is 4 t ha^{-1} but farmers have only realized production ranging from 0.8 up to 1.2 t ha^{-1} so far (MAFC, 2009) at the current average of 0.94 t ha^{-1} (FAOSTAT, 2012).

Understanding variability of crop production in agricultural systems due to dynamics in soil, nutrient, crop, management and weather processes and their interactions requires long term field experiments (Richter *et al*., 2007). However, few long-term field experiments exist with sufficient detail in space and time to test the best land management practices suitable for sustainable sorghum production. Previous studies on performance of sorghum varieties in Tanzania have been based on short-term field experiments both on-farm and on-station mainly testing isolated objectives.

Short-term field experiments though provide data with high degree of accuracy (Mugwe *et al*., 2009) suffer from the failure to capture the inter-annual variability due to environmental conditions. For instance, Hatibu *et al*. (1993) noted highest sorghum grain yield of 2.65 t ha^{-1} for var. Tegemeo under investigated treatments in the central zone of Tanzania, while Bucheyeki *et al*. (2010) observed that var. Tegemeo could give 2.58 t ha^{-1} and out-yielded *Macia*, *Pato* and *Wilu* varieties under fertilizer application rate of 46 kg N ha^{-1}and 18.4 kg P ha^{-}1. In contrast, however, results from on-station trials pooled across 14 locations in Tanzania during two consecutive growing seasons showed grain yields in the order of Macia>Pato>Tegemeo (Saadan *et al*., 2000). This is similar to on-farm trials at Same district, in northern Tanzania, conducted across three seasons, which showed that Pato and Macia were superior to Tegemeo (Saadan *et al*., 2000). Results from the afore-mentioned studies show that yields of improved varieties of sorghum vary among themselves and across locations and seasons. However, since the experiments are short lived, it is not possible to derive robust conclusions about the yield performance and adaptation of sorghum varieties over a long-term period.

Weather influences crop growth and development, causing large yield variability, mainly due to rainfall variability across seasons. Stone and Schlegel (2006) show that rainfall variability across years is an apparent determinant of the performance and adaptation of sorghum varieties, thus necessitating studies combining long-term period and multiple locations (spatial-temporal analysis) under variable rainfall and soils to elucidate their performance. Alongside such studies analyses of rainfall trends are deemed necessary to understand the vulnerability of semi-arid regions to historical and projected future conditions. Findings from a number of studies have shown decreasing trends (e.g. Silva, 2004; Batisani and Yarnal, 2010) associated with decreases in the number of rainy days, while others have revealed neither abrupt changes nor trends (Lazaro, *et al*., 2001). These contrasting results suggest the need for undertaking location specific analyses of rainfall trends to ascertain contentious assertions on the same. A combination of field experiments and computer simulation models could be an appropriate option to comprehend the biophysical (climatic and soil conditions) factors and their interactions affecting crop yield and productivity (Mathews *et al*., 2002; Challinor *et al*., 2009).

The Agricultural Production System sIMulator (APSIM) (Keating *et al*., 2003) is able to simulate growth and yield under different management practices for semi-arid environments (Mupangwa *et al*., 2011; Mkoga *et al*., 2010; Ncube *et al*., 2009). This study therefore used the APSIM model to simulate sorghum growth and yield patterns over the current (baseline) climate under existing soil conditions and local management practices across selected locations in semi-arid central Tanzania. Specifically, the study aimed to analyse trends of selected rainfall parameters, evaluate performance of sorghum varieties with respect to grain yield and to establish crop parameters for APSIM crop simulation model and to investigate the yield response of sorghum varieties across central Tanzania based on long-term weather records using simulation model.

2.2 Materials and methods

2.2.1 Study area

The central zone comprising Dodoma and Singida regions is located between latitudes 6^0 and 06^008' S and longitudes 34^030' and 35^0 45'E. The experimental site was located at Hombolo Agricultural Research Institute (ARI) in Dodoma region about 58 km North-East of Dodoma municipality at latitude 05^045'S and longitude 35^057'E. The mean annual rainfall is 589 mm but the distribution is highly variable (Ngana, 1991). The average annual temperature is 22.7^0C. Soils at the experimental site are mainly sandy and loamy of low fertility. They are classified as ferralic Cambisols in the FAO classification (Guzha *et al*., 2004).

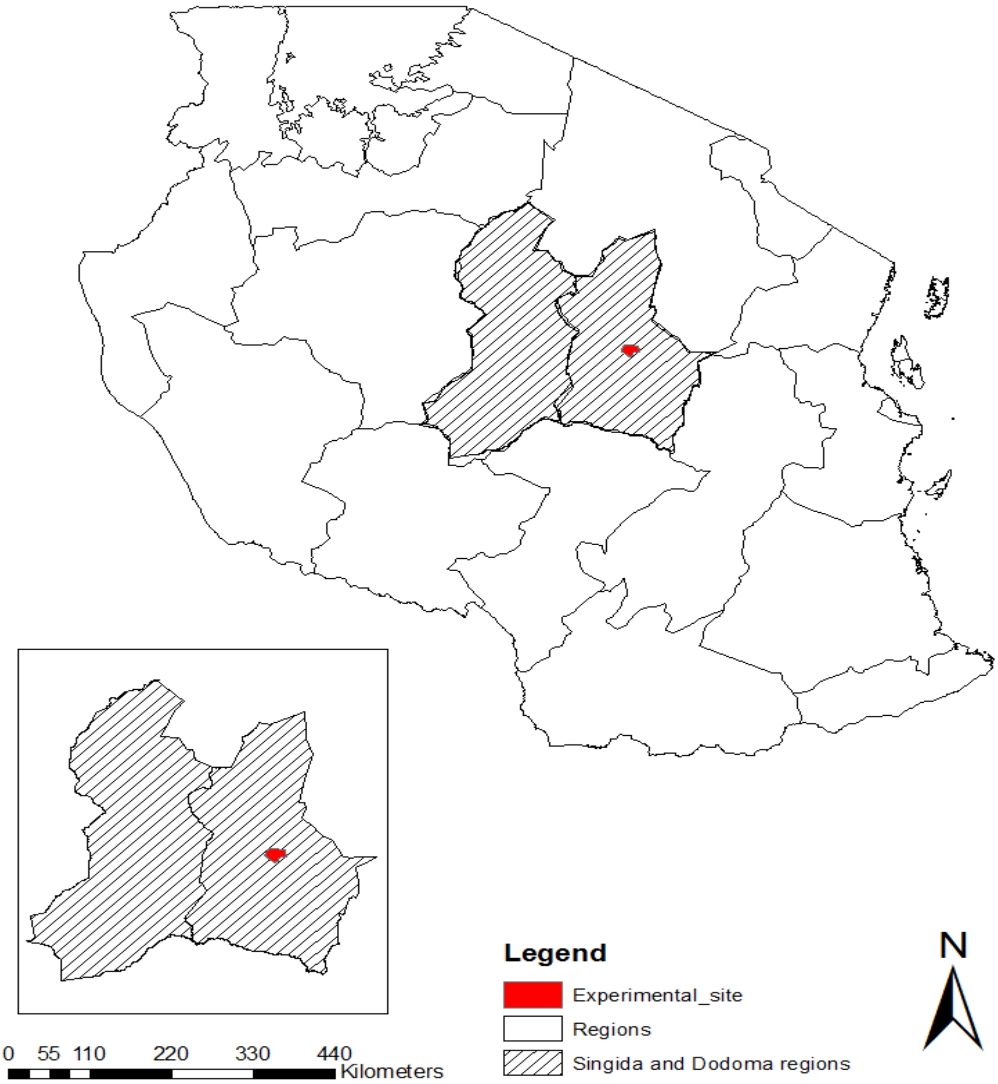


Figure 2.1 Map of Tanzania showing the location of Central zone and the field experimental site

2.2.2 Experimental design and data collection

Field experiments were conducted during 2012/13 and 2013/14 seasons. Three sorghum varieties namely, vars. Tegemeo, Macia and Pato (most widely grown varieties in the central zone) were used as treatments in a Randomized Complete Block Design (RCBD) with three replications. The three varieties were chosen due to their being stable and widely used in the central regions and the country at large. The recommended agronomic practices are similar for the three varieties. Planting in 2012/13 season was done on 4th January and during 2013/14 it was on 2nd January. Sowing was conditioned upon the previous day having received significant rainfall so as to wet the soil. Sorghum was sown at a spacing of 0.75 m between rows and 0.30 m within the row resulting in a plant density of 12 plants m^{-2}. About 20 mm and 15 mm of supplemental irrigation water were applied using watering cans on the 10 m x 5 m plots during the growing season whenever there was no rain for three consecutive days for 2012/13 and 2013/14 seasons, respectively (Table 2.1). Weeding was done manually three times on each plot using a hand hoe.

Table 2.1: Chronology of supplementary irrigation during the two growing seasons

2012/13		2013/14	
Date	Applied water (mm)	Date	Applied water (mm)
10-Feb-2013	2	9-Feb-2014	2
13-Feb-2013	2	16-Feb-2014	2
16-Feb-2013	2	22-Feb-2014	2
19-Feb-2013	2	25-Feb-2014	2
22-Feb-2013	2	1-Mar-2014	2
25-Feb-2013	2	6-Apr-2014	2
1-Mar-2013	2	7-Apr-2014	2
7-Mar-2013	2	10-Apr-2014	1
17-Mar-2013	1		
24-Mar-2013	1		
30-Mar-2013	1		
17-Apr-2013	1		

In order to provide near-optimum conditions, Diammonium phosphate (DAP) fertilizer was applied during planting to supply 25 kg P/ha and 40 kg N/ha, placed at approximately seven centimetres below the soil surface and covered and compacted with a soil layer, above which four to five seeds were placed to make a seeding depth of about 5 cm. Another round of N fertilization was done by applying 40 kg N/ha as Urea seven weeks after planting. Smallholder farmers rarely apply fertilizer on sorghum fields and according to Soil Fertility Report No. 6 (1993) no recommended fertilizer rates of N for sorghum in central Tanzania exist. The 80 kg N/ha was chosen for the sake of minimizing nutrient stress for the crop during the growing season from a blanket recommendation. The phenological data for the three sorghum varieties including date of flowering and date of physiological maturity were collected. These were noted when 50% of plant population in each plot had attained that respective stage.

Grain maturity was regarded to have been reached when dark spots at the point of attachment of the grain to the panicle started to show which was towards the end of April for both seasons. At final harvest, total above-ground biomass and grain yield were determined. Grain yield was determined by harvesting panicles from a 9 m^2 area. Sub-samples with known weight were dried at 70 ^{0}C to a constant weight. Dried weight of the sub-samples was used to determine the dry weight from the harvested area which was then expressed as t/ha. Above-ground biomass at maturity was harvested by cutting plants just above the surface of the ground and fresh weight noted. Sub-samples with known fresh weight were taken for each replicate and dried to a constant weight at 70 ^{0}C. Above-ground biomass per ha was then determined as in the case of grain yield. Harvest index was estimated as the ratio of grain yield to the total biological yield which is the yield obtained before any losses occur during and after harvest. Five plants from each plot were randomly selected for height measurement at maturity

2.2.3 Historical climatic trends

Daily weather data during both seasons were obtained from observations at an agro-met station, located about 500 m from the experimental plots. Past climate data (1961-2010) for selected weather stations, except Hombolo (1974-2010) in the central zone Tanzania, were analysed for trends. INSTAT plus (v3.36) software (Stern *et al*., 2006) was used to summarize the daily data into annual, monthly and seasonal totals and to determine the onset taken as the first occasion after the earliest possible date on which a running total of at least 20 mm of rain was reached in four consecutive days with at least two days being wet, and that no dry spell of 10 days or more occurred in the next 30 days (Kihupi *et al.,* 2007). Cessation of the rainy season was obtained through a water balance method and verified by visual daily display in INSTAT and length of growing period (LGP) was taken as the duration between the onset and cessation dates.

The Mann-Kendall test was used to test for significance of time series trends in total annual rainfall, seasonal rainfall, onset date, cessation date and LGP. The Mann-Kendall test is less sensitive to outliers and has the capability to detect both linear and non-linear trends, and has been used in related studies in sub-Saharan Africa (Mazvimavi, 2010; Hadgu *et al*., 2013). The median measure was used to show onset and cessation dates and days of LGP as it is relatively unaffected by extreme values compared to the mean.

The Mann-Kendall test statistic is given as:

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

(1)

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

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

(2)

For N larger than 10, Z_{MK} approximates the standard normal distribution (Yenigun *et al.,* 2008) and is computed as follows:

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

(3)

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

2.2.4 Model description, calibration and evaluation

The theory and parameterization of the APSIM (version 7.4) (Keating *et al*., 2003) model used in this study have been described in Ncube *et al*. (2009). APSIM has been tested in a diverse range of systems and environments, as well as model performance in long-term cropping systems in semi-arid and sub-humid environments in sub-Saharan Africa (Whitbread *et al*., 2010), including eastern Africa (Mkoga *et al*., 2010; Probert *et al*., 2004). The sorghum module used in the present study simulates the growth of a sorghum crop on a daily time step (on an area basis and not a single plant). Sorghum growth in this module responds to climate (temperature, rainfall and radiation from the met module), soil water supply (from the SoilWat module) and soil nitrogen (from the soiln module). Crop development is controlled by temperature (thermal degree days) and photoperiod. Thermal time accumulations were derived using an algorithm described in Jones and Kiniry (1986) using observed phenology and weather data, a base temperature of 8 ^{0}C and an optimal temperature of 30 ^{0}C. Genetic coefficients used by APSIM for sorghum are expressed in thermal degrees and photoperiod. The factor controlling the effect of photoperiod was set to a minimum value of 0.01 to eliminate the effect of photoperiod from the varieties as "modern" varieties are photoperiod insensitive (Kouressy *et al*., 2008). In the present study, the APSIM model was evaluated for simulation of days after sowing to flowering and maturity, dry matter accumulation (biological yield) and grain yield.

Soil water dynamics between soil layers were defined by the cascading water balance method (Ritchie, 1998). Its characteristics in the model are specified by the drained upper limit (DUL), lower limit of plant extractable water (LL15) and saturated water content (SAT). Soil characteristics of a soil profile opened up at the site including soil texture (clay, silt and sand contents), pH of soil, organic carbon content and cation exchange capacity are shown in Table 2.2. Characteristics for the additional soil profiles used in simulations at different locations across the study area were obtained from the available soil databases. The profile descriptions are considered as representative of soil conditions in the selected locations. One soil profile was created for each location and a summary of the key characteristics of the profiles is presented in Table 2.3. Each APSIM module demands a number of parameters. For the SOILWAT module, which simulates the dynamics of soil water, the inputs included soil bulk density, LL15 and DUL, and two parameters, *U* and *CONA*, which determine first and second stage soil evaporation. LL15 and DUL and SAT were estimated according to Saxton *et al*. (1986). The parameters, *U* and *CONA* were set at 6.0 mm day-1 and 3 mm day-1, respectively, values acceptable for tropical conditions (Chikowo, 2011). A value of 0.7 was used for *SWCON*, a coefficient that specifies the proportion of the water in excess of field capacity that drains to the next layer in one day (Chikowo, 2011). The bare soil runoff curve number (cn2_bare) was set to 50 to account for the low runoff because of the flat topography and high infiltration rates due to the sandy soil nature of the experimental site (Hussein, 1987 cited by Rurinda *et al*., 2014). Parameters influencing soil fertility are mainly represented in APSIM-SoilN2 module. For the soil N model the organic carbon content for each soil layer was measured at the experimental site. The initial soil N was set at 25 kg/ ha (20 kg NO_3-N/ ha and 5 kg NH_4+-N/ ha) for the top two layers based on published data around central Tanzania (Pierce *et al*., 2003), and P was assumed non-limiting.

Table 2.2: Soil physical and chemical properties used for the calibration of APSIM

Soil parameters	Layers					
	150mm[a]	150mm[a]	150mm[a]	250mm[a]	350mm[a]	300mm[a]
BD (g cm^{-3})	1.38	1.47	1.44	1.38	1.51	1.51
SAT (cm cm^{-1})	0.37	0.35	0.34	0.33	0.33	0.33
LL (cm cm^{-1})	0.084	0.084	0.134	0.134	0.134	0.14
DUL (cm cm^{-1})	0.248	0.299	0.334	0.278	0.270	0.270
Clay (%)	19	20	23	25	34	30
Silt (%)	5	4	4	5	2	4
CEC (cmol/kg)	6.0	8.2	9.2	10.2	10.0	6.0
Soil C parameters						
Organic C (g 100 g^{-1})	0.41	0.31	0.23	0.14	0.14	0.06
Finert[b]	0.4	0.6	0.8	0.8	0.9	0.9
Fbiom[c]	0.025	0.02	0.015	0.01	0.01	0.01

BD: bulk density; SAT: volumetric water content at saturation. LL is wilting point (volumetric water content at -15 bar pressure potential) and DUL is drained upper limit.
[a] Layer thickness (mm)
[b] Proportion of soil carbon assumed not to decompose
[c] Proportion of decomposable soil carbon in the more labile soil organic matter pool.

Table 2.3: Soil properties of the profiles used in simulations across stations

Properties	Dodoma	Hombolo	Mpwapwa	Manyoni	Singida
Soil layers/depth (cm)	6/135	6/135	4/110	4/115	4/110
Sand, silt, clay (% in 0-15cm)	79,5,16	79,5,16	81,6,13	66,10,14	55,21,24
Textural class	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy clay loam
Plant available water	119.2	119.2	112.8	164.1	162.1
Organic carbon (top three layers)	0.32,0.21, 0.11	0.32,0.21, 0.11	0.45,0.30, 0.15	0.56, 0.32, 0.12	0.52, 0.38, 0.20

The calibrated model was evaluated by comparing observed values for grain yield and total above-ground biomass with those from model simulations. Model performance was assessed through root mean square error (RMSE) (Wallach, 2006),

$$RMSE = \sqrt{\frac{1}{N}\Sigma\left(\hat{Y}i - Yi\right)^2} \qquad (4)$$

and index of agreement or d-statistic (Willmott, 1985),

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(\hat{Y}i - Yi)(\hat{Y}i - Yi)}{\sum_{i=1}^{n}\left(\left|\hat{Y}i - \bar{Y}i\right| + \left|Yi - \bar{Y}i\right|\right)}\right] \qquad (5)$$

Where $\hat{Y}$, Y and $\bar{Y}$ are respectively, the simulated, observed and mean of the observed values and n is the number of observations. For good agreement between model simulations and observations, *d*-statistic should approach unity.

2.2.5 Statistical analysis

Analysis of variance (ANOVA) was used to analyse yield and total biomass data from the different treatments. Test of significance between the 2012/2013 and 2013/2014 experiments was done using a t-test for pair-wise comparison of means. Analysis of variance was performed using GENSTAT (v. 14) software (VSN international Ltd., Hempstead, England) whereas paired t-test was performed using Microsoft Excels' add-in Analyse-it (Analyse-it Software Ltd., The Tannery, 91 Kirkstall Road Leeds, LS31HS, United Kingdom).

2.3 Results and discussion

2.3.1 Trend analyses of annual and seasonal rainfall

The Mann–Kendall's test results show tendencies of decreasing trends in some stations and increasing trends in others in annual and seasonal rainfall, but the trends are not statistically ($p = 0.05$) significant (Table 2.4). All stations show an increasing trend for annual rainfall. For seasonal rainfall (i.e. amount accumulated during the period from onset to cessation), all stations except Manyoni show non-statistically significant increasing trends. Lema and Majule (2009) gave graphical presentations of rainfall trends (1922 - 2007) for Manyoni and Singida revealing decreasing trends of annual and seasonal rainfall without a clear indication of the significance of the results. Kassile (2013) observed non-statistically significant decreasing trends in the amount of rainfall in Dodoma region over the last 30 years (1980 - 2010) using both parametric and non-parametric analytical methods. However, results of analyses in current study over 49 years (1961 - 2010) indicate a general non-statistically significant increasing trend in both annual and seasonal rainfall across all stations, except Manyoni which show a decreasing trend.

2.3.2 Trends in onset and cessation dates and length of growing period

The median for onset of rainfall begins on the last week of November to first week of December (Table 2.5). Standard deviation varied between 11-15 days. The results indicated that the onset dates in the last 50 years have changed with all stations depicting early trends. However, the trends are not statistically significant except for Hombolo station. According to the analysed data, cessation of rainfall start from the first week of April (at Hombolo) to last week of April (at Singida) (Table 2.5). Munishi (2009) also reported similar findings in central Tanzania with slightly earlier onset and cessation dates. The median date for rainfall cessation was characterized by high standard deviation (>10 days) at all stations implying high variability in the pattern of end of the rainy season. However, these results are contrary to other studies which have shown less variable cessation dates than onset dates (e. g. in Camberlin and Okoola, 2003 (1961-2001) and Kihupi *et al.*, 2007 (1961-2001).

Median LGP in the central Tanzania varied from 122-145 days depending on the location of the station (Table 2.5). All stations had higher coefficients of variation (>13%) in LGP which indicate high year to year variability of LGP except for

Dodoma (12%). Higher coefficients of variation (>13%) in LGP, gives less confidence in crop selection based on maturity period. From the analyses, a mix of increasing and decreasing trends in LGP was obtained. Singida and Hombolo stations show statistically significant increasing trends in LGP (Table 2.5) different from Dodoma, Mpwapwa and Manyoni stations which all show decreasing trends in LGP although the trends are not statistically significant.

Table 2.4: Trends of annual and seasonal rainfall totals in central Tanzania for the period 1961 -2010

Station	Annual		Seasonal	
	Z_{MK}	Slope	Z_{MK}	Slope
Dodoma	1.271 ns	1.536	0.972 ns	1.178
Mpwapwa	0.381ns	0.503	0.147 ns	0.452
Hombolo	0.123 ns	0.655	0.749 ns	1.819
Manyoni	0.750 ns	1.447	-0.043 ns	-0.075
Singida	1.388 ns	2.593	0.905 ns	1.674

Z_{MK} is Mann–Kendall trend test, Slope (Sen's slope) is the change (days)/annum; *, is statistically significant at 0.05 probability level; ns is non-significant trend.

Table 2.5: Statistical characteristics and trends of onset date, cessation date and LGP at five stations over the period 1961-2010 in Central Tanzania

Station		Dodoma	Mpwapwa	Hombolo	Manyoni	Singida
	Statistics					
Onset	Median	Dec-13	Dec-7	Dec-7	Dec-1	Nov-26
	Z_{MK}	-0.07ns	-0.030 ns	-1.196 *	-0.911 ns	-0.680 ns
	Slope	0.00	-0.091	-0.321	-0.225	-0.131
	SD	11.311	14.252	14.870	14.361	14.582
Cessation	Median	Apr-18	Apr-13	Apr-5	Apr-14	Apr-30
	Z_{MK}	-0.337 ns	-1.188ns	0.970 ns	-0.755 ns	1.692 *
	Slope	0.000	-0.083	0.029	-0.070	0.303
	SD	10.252	16.041	11.054	14.281	16.711
LGP (days)	Median	124	122	123	141	145
	Z_{MK}	-0.303 ns	-0.419 ns	2.092 *	-0.480 ns	1.876 *
	Slope	0.000	-0.067	0.434	0.000	0.692
	CV (%)	12.510	13.711	14.281	13.511	15.982

Z_{MK} is Mann–Kendall trend test, Slope (Sen's slope) is the change (days)/annum; *, is statistically significant at 0.05 probability level; ns is non-significant trend; SD is standard deviation; CV is coefficient of variation.

The three stations agree with findings from earlier studies which show that LGP has been shortening with a decreasing trend of number of rainy days during the growing season in semi-arid areas such as parts of the Central plateau (Lema and Majule, 2009; Munishi, 2009; Kihupi *et al*., 2007).

2.3.3 Field experimental results

Summary of temperature records during the growing seasons are shown in Table 2.6. Cumulative rainfall for the two seasons (2012/13 and 2013/14) at the experimental site during the growing period are shown in Fig. 2.1. More rain was accumulated during the early stages of the crop in 2012/13 than in 2013/14. However, during the later stages of the crop from 45 days after planting onwards the cumulative rain was higher in 2013/14. The differences in cumulative rain for the two seasons are attributed to total monthly rainfall for January and February. The month of January during the 2012/13 season had higher amount (213mm) of rainfall than during 2013/14 season (138mm). The month of February had lower amount of rainfall (33.1mm) during 2012/13 cropping season as a result of a dry spell of more than three weeks (27^{th} Jan – 21^{st} Feb) than during the 2013/14 season where the amount was 87.7mm. Overall the two season's rainfall distribution indicates the ongoing rainfall variability which strongly influences growth and development of rain-fed cereals.

Table 2.6: Mean seasonal maximum and minimum temperature at Hombolo, Dodoma Tanzania

Month	2012/13 Maximum temperature (°C)	Minimum temperature (°C)	2013/14 Maximum temperature (°C)	Minimum temperature (°C)
December	31.3	20.1	31.0	20.0
January	30.6	20.4	30.3	19.8
February	31.8	20.0	29.6	19.6
March	30.6	20.0	29.7	19.0
April	30.1	19.4	29.1	18.9
May	29.2	17.8	29.0	16.8

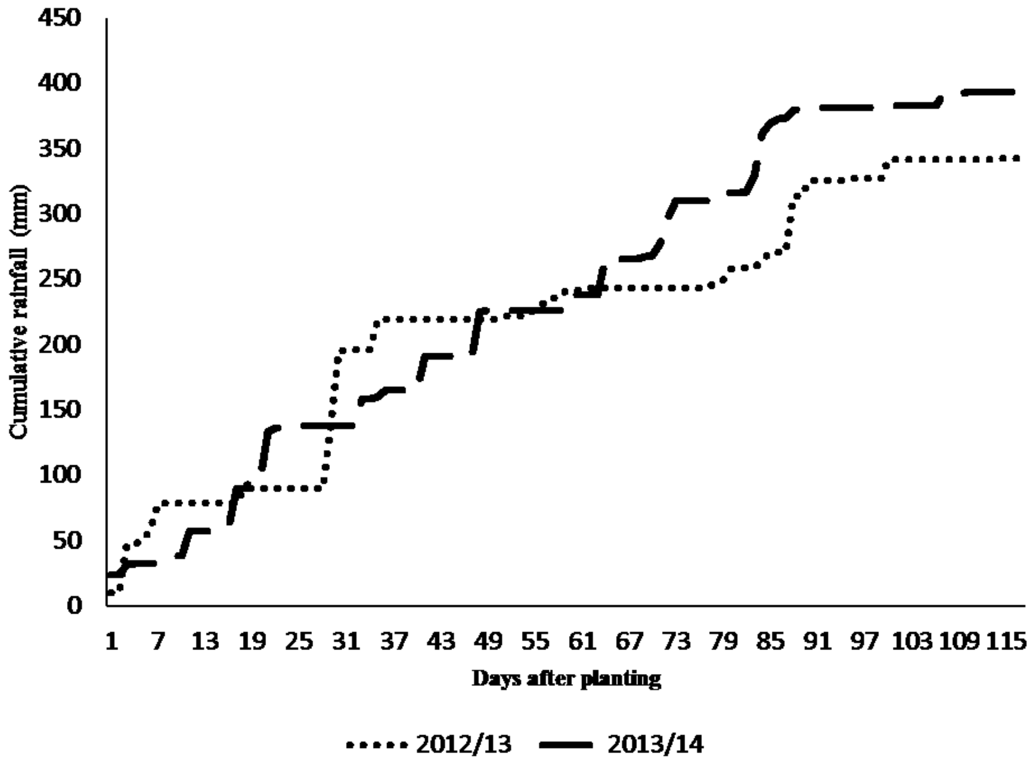


Figure 2.2 Cumulative quantities of rain over two seasons

Variable grain yields obtained during the two experimental seasons could largely be explained by rainfall distribution in spite of applying supplemental irrigation during both seasons (Table 2.7). There was better distribution of rainfall in the second than in the first season. This occurred especially during the month of February in

2013/2014 which had fewer days of dry spells compared to a three week dry spell which occurred in 2012/2013. Similarly, Mesfine *et al.* (2005) and Stone and Schlegel (2006) reported that sorghum yields variation is dependent on rainfall distribution between years.

Table 2.7: Grain yield, aboveground biomass and harvest index for seasons 2012/13 and 2013/14

Variety	**2012/13**			**2013/14**			**Combined seasons**		
	Grain yield (kg/ha)	Aboveground biomass (kg/ha)	HI	Grain yield (kg/ha)	Aboveground biomass (kg/ha)	HI	Days to 50% flowering	Days to Harvest maturity	Plant height (max) mm
Macia	4064*	10517	0.39	4355	11388	0.38	65	102	1290
Pato	3896	11411	0.34	4088	12394	0.33	76	118	1780
Tegemeo	3798	10843	0.35	4012	11415	0.35	74	114	1650
S.E.D	233.9	274.3	0.018	79.1	100.7	0.02	0.577	0.471	147.1

* = Means over three replications. S.E.D = standard error of differences of means

Harvest index (HI) which is the ratio of harvested grain to total shoot dry matter in grain crops can be used as a measure of reproductive efficiency. Kusalkar *et al.* (2003) indicate that the higher the HI the higher the efficiency of converting biological yield into economic yield. Harvest indices obtained in the present study are in the range of 0.38-0.39, 0.35-0.36 and 0.34-0.36 for vars. Macia, Tegemeo and Pato, respectively. Other studies have reported higher harvest indices of sorghum. For example, Hammer and Broad (2003) reported a HI between 0.47 and 0.57 for grain sorghum when grown under non-limiting water and N conditions. On the other hand, Patil (2007) reported HI ranging from 0.26 to 0.36 for sorghum varieties in India. There was no significant variation among varieties in the 2012/2013 season with respect to biomass at 50% anthesis, biomass at harvest maturity and grain yield (Table 2.8). However, during the season of 2013/2014, significant variation ($P<0.05$) in the three variables was observed among varieties. Further, there was inter seasonal variation in plant biomass at 50% anthesis, grain yield and biomass at harvest as indicated by the t-statistic in Table 2.8.

Table 2.8: Intra- and inter-seasonal variation in biomass, grain yield and tops weight

Variable	2012/2013	2013/2014	t-statistic
Biomass at 50% anthesis	2.77 ^{ns}	5.49 *	3.89**
Grain yield at harvest	1.41 ^{ns}	21.08 *	5.08 *
Biomass at harvest maturity	3.23^{ns}	50.49 *	8.60 *

*significant at p<0.05; **significant at p<0.01 ns = not significant

2.3.4 Model calibration and evaluation

Genetic coefficients used by APSIM for sorghum after calibration are shown in Table 2.9. Comparison between observed and simulated grain and biomass yield combined for the two seasons is shown in Table 2.10. Statistical indicators show the simulation efficiency of APSIM model in simulating sorghum. Root mean square error (RMSE) which is an overall measure of model performance and compares simulated versus observed values shows a good agreement because the lower the values of RMSE the better the model in explaining most of the variations in the dataset.

Table 2.9: Crop parameters for three sorghum cultivars used for the simulations in APSIM

Parameter		Source	Units	Macia	Tegemeo	Pato
Thermal time accumulation	End of juvenile phase to panicle initiation	C	^{0}C day	230	270	275
	Flag stage to flowering	C	^{0}C day	195	170	175
	Flowering to start of grain filling	C	^{0}C day	80	80	100
	Flowering to maturity	C	^{0}C day	675	760	760
	maturity to seed ripening	L	^{0}C day	1	1	1
Photoperiod	Day length photoperiod to inhibit flowering	D	h	11.5	11.5	11.5
	Daylength photoperiod for insensitivity	D	h	13.5	13.5	13.5
	Photoperiod slope	L	^{0}C/h	0.01	0.01	0.01
	Base temperature	L	^{0}C day	8	8	8
	Optimum temperature	D	^{0}C day	30	30	30
	Plant height (max)	O	mm	1290	1650	1780

C: calibrated; D: Default; L: literature; O: observed

Moreover, data indicate that the simulated grain and biomass yield values reasonably matched observed values, owing to the agreement index (d-statistic) ranging from 0.6 to 0.9 across the varieties. The d-statistic values close to 1 are regarded as better simulations and according to these statistical indicators the model performance was deemed satisfactory to allow continuation of simulations for both long-term (temporal) and at different locations (spatial).

Table 2.10: Statistical indicators of model performance

Parameters/ Cultivar	Macia		Tegemeo		Pato	
	RMSE (kg/ha)	d-Stat	RMSE (kg/ha)	d-Stat	RMSE (kg/ha)	d-Stat
Grain yield	133	0.73	87	0.62	140	0.60
Biomass	178	0. 93	418	0.66	236	0.83

2.3.5 Influence of water stress on sorghum grain yield

Simulated grain yields for the three varieties at the experimental station are shown in Fig. 2.3. The simulation package consisted: planting between 15 December to 15 January, a row spacing of 0.90 m and a population of 9 plants per m^2 without N fertilizer under baseline weather (1980-2010). Results indicated that simulated yields varied among varieties with the range of 2.65 - 2.88 t ha^{-1} for the highest yields, and 0.48 - 0.57 t ha^{-1} for the lowest yields.

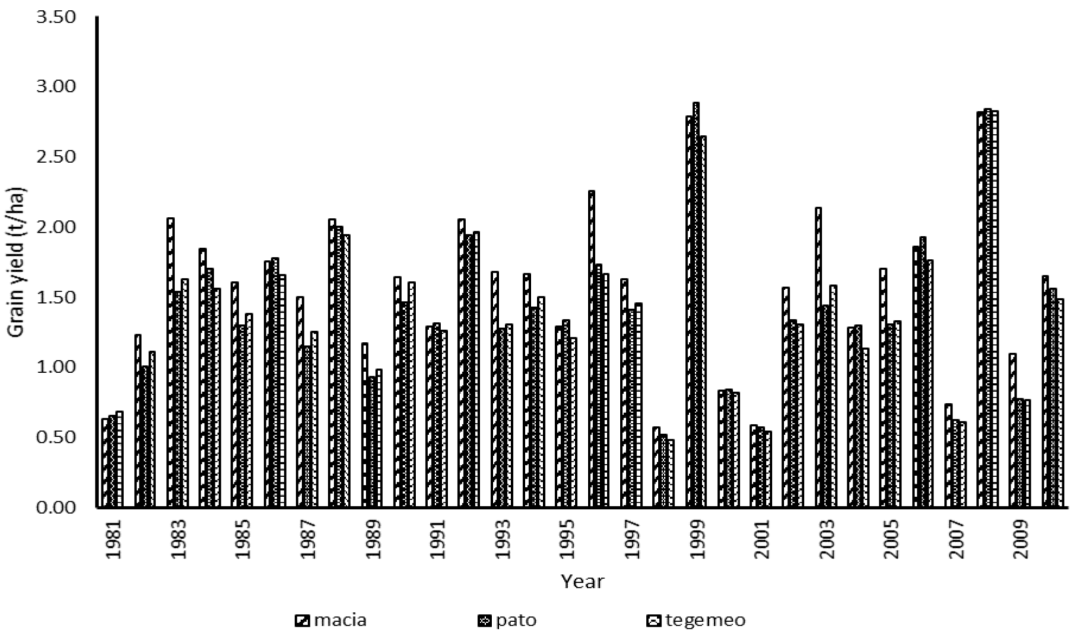


Figure 2.3: Simulated grain yield of Macia, Pato and Tegemeo sorghum varieties under baseline (1980-2010) conditions at Hombolo

Rainfall being one of the most important weather parameters in crop yield simulations deserves a closer look for a better understanding of the rainfall-yield interaction. Crop yield simulations at different locations (weather stations) across the central zone of Tanzania were temporally correlated (1980-2010) with the seasonal total rainfall amounts as shown in Table 2.11. Taking into account uniform farmers' management practices across the study area, the multi-location simulated crop yields may be explained by the response of the crop to inter and intra-rainfall variability. Variability of seasonal rainfall total explains crop yields by 18% and above at two stations namely Mpwapwa and Manyoni, and less than 18% for the other stations.

Hence, a good seasonal rainfall forecast can capture approximately 30% (e.g. for Mpwapwa) of the variability of crop yields.

Table 2.11: Temporal correlation coefficients between the simulated crop yields and the corresponding seasonal rainfall amounts

Variety	Hombolo	Mpwapwa	Manyoni	Singida
Macia	-0.04	0.35	-0.29	0.02
Tegemeo	-0.01	0.28	-0.26	0.08
Pato	-0.02	0.29	-0.18	0.13

Further examination of rainfall and yields in 1998 (the year producing lowest simulated yields) and 2008 (the year producing highest simulated yields) demonstrates the importance of rainfall distribution during the growing period and especially during critical stages. There was approximately 0.50 t ha^{-1} maize yield in 1998 compared to 2.80 t ha^{-1} in 2008 (Fig. 3). This was probably due to water stress. It means that yields simulated by APSIM are highly sensitive to wet/dry-spell sequences during the crop growing season. Baigorria *et al*. (2007) observed that not only increasing persistence of wet/dry day occurrences is important, but also the timing within the growing season when these wet/dry spells occurred. Decadal analyses of rainfall for occurrences of 5 and 10-day dry spells shown in Table 2.12 indicate that in 1998 the occurrence of a 10-day dry spell during the first decade in March caused strong water stresses which significantly reduced sorghum grain yields. On the contrary sorghum experienced only a brief water stress period (5-day dry spell during the same period) as a result much higher yields were obtained in 2008. According to the sowing dates in the simulation package, the period represents the crop growth stages from flag leaf appearance to start of grain filling.

Premachandra *et al*. (1994) noted that as the most sensitive period for sorghum response to drought among phenological phases.

Table 2.12: Occurrences of dry spells during March and April and their relationship to simulated grain yields at Hombolo

	YEARS WITH LOWEST YIELDS												YEARS WITH HIGHEST YIELDS											
	1998						2001						1999						2008					
	MAR			APR			MAR			APR			MAR			APR			MAR			APR		
DECADE	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
5-DAY		√						√	√	√		√			√	√	√	√	√	√				
10-DAY		√						√				√						√						
Yield (t/ha)	0.48 -0.57						0.54 – 0.58						2.65 – 2.88						2.82 -2.84					
Rain (mm)		38.8			98.9			66.4			63.2			211.6			117			182.1			42.3	
Rainy days		6			8			6			8			12			5			10			11	

√ indicate occurrence of a dry spell in a decade (10-day interval) within a month

2.4 Conclusions

Sorghum grain yields response was investigated both under field and simulated conditions. The field experimental results for the two seasons show considerable variations in grain yields among varieties. An early maturing variety Macia gave higher yields in both seasons compared to vars. Pato and Tegemeo. Model simulated yields reveal that, the length and timing of dry/wet spells during the growing season are more important than total seasonal rainfall amount even for a hardy crop like sorghum. Results seem to suggest that occurrence of a long dry spell (10-day or longer) during the period from flag leaf appearance to start of grain filling is critical and could significantly reduce yield. Simulation results under current (baseline) climatic conditions at different locations indicate that the rainfall variability could explain approximately 30% of inter-annual yield variability. This means that other non-climatic factors play a significant role in resulting grain yield determination. The phenological characterization of the three varieties and subsequent calibration and validation of APSIM have provided a basis on which various kinds of simulations could be done with the aim to increase and sustain sorghum productivity.

2.5 REFERENCES

Baigorria, G. A., Jones, J. W., Shin, D. W., Mishra, A. and O'Brien, J. J. (2007). Assessing uncertainties in crop model simulations using daily bias-corrected regional circulation model outputs. *Climate Research* 34: 211 – 222.

Batisani, N. and Yarnal, B. (2010). Rainfall variability and trends in semi-arid Botswana: Implications for climate change adaptation policy. *Applied Geography* 30: 483 – 489.

Bucheyeki, T. L., Shenkalwa, E. M., Mapunda, T. X. and Matata, L. W. (2010). Yield performance and adaptation of four sorghum cultivars in Igunga and Nzega districts of Tanzania. *Communications in Biometry and Crop Science* 5 (1): 4 – 10.

Camberlin, P. and Okoola, R. E. (2003). The onset and cessation of the ''long rains'' in Eastern Africa and their interannual variability. *Theoretical Applied Climatology* 75: 43 – 54.

Challinor A. J., Ewert, F., Arnold, S., Simelton, E. and Fraser, E. (2009). Crops and climate change: progress, trends and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany* 60: 2775 – 2789.

Chikowo, R. (2011). Climatic risk analysis in conservation agriculture in varied biophysical and socio-economic settings of southern Africa. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Craufurd, P. Q., Mahalakshmi, V., Bidinger, F. R., Mukuru, S. Z., Chantereau, J., Omanga, P. A., Qi, A., Roberts, E. H., Ellis, R. H., Summerfield, R. J. and Hammer, G. L. (1999). Adaptation of sorghum: characterisation of genotypic flowering responses to temperature and photoperiod. *Theoretical and Applied Genetics* 99(5): 900 – 911.

FAOSTAT (2012). (Available at http://faostat.fao.org/, updated 07 February, 2014)

Garofalo, P. and Rinaldi, M. (2013). Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment. *Spanish Journal of Agricultural Research* 11(4): 1153 – 1169.

Guzha, A. C. (2004). Effects of tillage on soil micro relief, surface depression storage and soil water storage. *Soil and Tillage Research* 76: 105 – 114.

Hadgu, G., Tesfaye, K., Mamo, G. and Kassa, B. (2013). Trend and variability of rainfall in Tigray, Northern Ethiopia: Analysis of meteorological data and farmers' perception. *Academia Journal of Agricultural Research* 1: 088 - 100.

Hammer, G. L. and Broad, I. J. (2003). Genotype and Environment Effects on Dynamics of Harvest Index during Grain Filling in Sorghum. *Agronomy Journal* 95: 199 - 206.

Hatibu, N., Mahoo, H. F., Senkondo, E. M., Simalenga, T. E., Kayombo, B., Ussiri, D. A. N. and Mwaseba, D. (1993). Strategies for soil-water management for dryland crop production in semi-arid Tanzania. In: *Proceedings of Tanzania Society of Agricultural Engineers*. (Edited by Hatibu, N. *et al.*), 5 - 7 April 1993, Morogoro, Tanzania. 83 – 97pp.

Jones, C. A. and Kiniry, J. (1986). CERES-Maize: a simulation model of maize growth and development. Texas A and M University Press, College station, TX

Kassile, T. (2013). Trend analysis of monthly rainfall data in central zone. *Journal of Mathematics and Statistics* 9: 1-11.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Reebairn, D. M. and Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy* 18: 267 – 288.

Keya, S. and Rubaihayo, P. (2013). *Progress in On-Farm Production and Productivity in the East African Community: 50 Years after Independence.* Kilimo Trust Technical Paper No.8. International Symposium on Agriculture: EAC partner states at 50years 5-7 November, 2013. 56pp.

Kihupi, N. I., Tarimo, A. K. P. R. and Dihenga, H. O. (2007). Spatial and temporal variation of growing season characteristics in Tanzania. *Journal of the Geographical Association of Tanzania* 32: 33 – 49.

Kouressy, M., Dingkuhn, M., Vaksmann, M. and Heinemann, A. B. (2008). Adaptation to diverse semi-arid environments of sorghum genotypes having different plant type and sensitivity to photoperiod. *Agricultural and Forest Meteorology* 148: 357 - 371.

Kusalkar, D. V., Awari, V. R., Pawar, V. Y. and Shinde, M. S. (2003). Physiological parameters in relation to grain yield in rabi sorghum on medium soil. *Advances in Plant Sciences* 16: 119 – 122.

Lazaro, R., Rodrigo, F. S., Gutierrez, L., Domingo, F. and Puigdefabregas, J. (2001). Analysis of a 30 year rainfall record (1967–1997) in semi-arid SE Spain for implications on vegetation. *Journal of Arid Environments* 48: 373 – 395.

Lema, M. A. and Majule, A. E. (2009). Impacts of climate change, variability and adaptation strategies on agriculture in semi-arid areas of Tanzania: The case of Manyoni District in Singida Region, Tanzania. *African Journal of Environmental Science and Technology* 3(8): 206 - 218.

Makindara, J. R., Hella, J. P., Erbaugh, J. M. and Larson, D. W. (2013). Consumer preferences and market potential for sorghum based clear beer in Tanzania. *Journal of Brewing and Distilling* 4: 1 - 10.

Maredia, M. K., Byerlee, D. and Pee, P. (2000). Impacts of food crop improvement research: evidence from Sub-Saharan Africa. *Food Policy* 25: 531 - 559.

Mathews, R., Stephens, W., Hess, T., Middleton, T. and Graves, A. (2002). Applications of crop/soil simulation models in tropical agricultural systems. *Advances in Agronomy* 76: 31 - 124.

Mazvimavi, D. (2010). Investigating changes over time of annual rainfall in Zimbabwe. *Hydrology and Earth System Sciences* 14: 2671 - 2679.

Mesfine, T., Abebe, G. and Al-Tawaha, A. M. (2005). Effect of reduced tillage and crop residue ground cover on yield and water use efficiency of sorghum (*Sorghum bicolor* L. Moench) under semi-arid conditions of Ethiopia. *World Journal of Agricultural Sciences* 1: 152 – 160.

Mkoga, Z. J., Tumbo, S. D., Kihupi, N. and Semoka, J. (2010). Extrapolating effects of conservation tillage on yield, soil moisture and dry spell mitigation using simulation modelling. *Physics and Chemistry of the Earth Parts A/B/C* 35: 686 - 698.

Monyo, E. S., Ngereza, J., Mgonja, M. A., Rohrbach, D. D., Saadan, H. M. and Ngowi, P. (2004). Adoption of improved sorghum and pearl millet technologies in Tanzania. Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics. 28 pp.

Mugwe, J., Mugendi, D., Kungu, J. and Muna, M. M. (2009). Maize yields response to application of organic and inorganic input under on-station and on-farm experiments in central Kenya. *Experimental Agriculture* 45: 47-59.

Munishi, P. K. T. (2009). Analysis of climate change and its impacts on productive sectors, particularly agriculture in Tanzania. Report submitted to the Ministry of Finance and Economic Affairs. 72pp.

Mupangwa, W., Dimes, J., Walker, S. and Twomlow, S. (2011). Measuring and simulating maize (*Zea mays* L.) yield responses to reduced tillage and mulching under semi-arid conditions. *Agricultural Sciences* 2(3): 167 - 174.

Murty, M. V. R., Piara, S., Wani, S. P., Khairwal, I. S. and Srinivas, K. (2007). Yield Gap Analysis of Sorghum and Pearl Millet in India Using Simulation Modelling. Global Theme on Agro ecosystems Report no. 37. Patancheru, Andhra Pradesh, India. International Crops Research Institute for the Semi-Arid Tropics. 82pp.

Ncube, B., Dimes, J. P., van Wijk, M., Twomlow, S. and Giller, K. (2009). Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south- western Zimbabwe: Unravelling the effects of water and nitrogen using a simulation model. *Field Crops Research* 110: 173 - 184.

Ngana, J. O. (1991). Selection of probability distribution for estimating reliability seasonal rainfall in Semi-arid Central Tanzania. IRA paper no. 79, UDSM. 28pp.

Patil, S. L. (2007). Performance of sorghum varieties and hybrids during post-rainy season under drought situations in Vertisols in Bellary, India. *Journal of SAT Agricultural Research* 5(1): 45 – 56.

Pierce, S., Mbwaga, A. M., Ley, G., Lamboll, R. I., Riches, C. R., Press, M. C., Scholes, J. D. and Watling, J. (2003). Chemical characteristics of soil and sorghum from *Striga*-infested regions of Tanzania, and the influence of fertiliser application. Sheffield, UK: University of Sheffield. 29pp.

Premachandra, G. S., Hahn, D. T. and Joly, R. J. (1994). Leaf water relations and gas exchange in two grain sorghum genotypes differing in their pre- and post-flowering drought tolerance. *Journal of Plant Physiology* 143: 96 – 101.

Probert, M. E., Delve, R. J., Kimani, S. K. and Dimes, J. P. (2004). The APSIM Manure Module: Improvements in Predictability and Application to Laboratory Studies. In: *ACIAR Proceedings No. 114*. Modelling Nutrient Management in Tropical Cropping Systems. (Edited by Delve, R. J. and Probert, M. E.), Canberra, Australia. 76 – 84pp.

Richter, D., Hofmockel, M., Callaham, M. A., Powlson, D. S. and Smith, P. (2007). Long-term soil experiments: keys to managing earth's rapidly changing ecosystems. *Soil Science Society of American Journal* 71: 266 - 279.

Ritchie, J. T. (1998). Soil Water Balance and Plant Water Stress. In: *Understanding Options for Agricultural Production. (Edited by Tsuji Y., Tsuji, G. Y., Hoogenboom, G. and Thornton, P. K.*), Kluwer Academic Publishers, Dordrecht. pp. 45 - 58.

Rurinda, J., Mapfumo, P., van Wijk, M. T., Mtambanengwe, F., Rufino, M. C., Chikowo, R. and Giller, K. E. (2014). Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *European Journal of Agronomy* 55: 29 - 41.

Saadan, H. M., Mgonja, M. A. and Obilana, A. B. (2000). Performance of the Sorghum variety *Macia* in Multiple Environments in Tanzania. 18pp.

Saxton, K. E., Rawls, W. J., Romberger, J. S. and Papendick, R. I. (1986). Estimating generalized soil-water characteristics from texture. *Soil Science Society of American Journal*. 50: 1031 - 1036.

Silva, V. P. R. (2004). On climate variability in Northeast of Brazil. *Journal of Arid Environments* 58: 575 - 596.

Stern, R., Rijks, D., Dale, I. and Knock, J. (2006). INSTAT (interactive statistics) climate guide. pp. 330.

Stone, L. R. and Schlegel, A. J. (2006). Yield-water supply relationships of grain sorghum and winter wheat. *Agronomy Journal* 98: 1359 – 1366.

Wallach, D. (2006). Evaluating crop models. In: *Working with Dynamic Crop Models Evaluation, Analysis, Parameterization, and Applications*. *Edited by Wallach, D., Makowski, D. and Jones, J. W.*). Elsevier, Amsterdam. pp. 11 - 54.

Whitbread, A. M., Robertson, M. J., Carberry, P. S. and Dimes, J. P. (2010). How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa. *European Journal of Agronomy* 32: 51 – 58.

Willmott, C. J., Akleson, G. S., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., Odonnell, J. and. Rowe, C. M. (1985). Statistics for the evaluation and comparison of models. *Journal of Geophysical Research* 90: 8995 – 9005.

Yenigun, K., Gumus, V. and Bulut, H. (2008). Trends in stream flow of the Euphrates basin, Turkey. *Water Management* 161: 189 – 198.

CHAPTER THREE

3.0 IMPACTS OF CLIMATE CHANGE ON RAINFED SORGHUM AND MAIZE: IMPLICATIONS FOR FOOD SECURITY POLICY IN TANZANIA

ABSTRACT

Concern about food security has increased because of a changing climate, which poses a great threat to food crop productivity. Climate change projections from the Coupled Model Inter-comparison Project phase 5 (CMIP5) and crop models were used to investigate the impacts of climate change on rain-fed cereal production. Calibrated and evaluated crop models simulated maize and sorghum yields over time periods and scenarios across central zone Tanzania with and without adaptation. Simulation outputs without adaptation showed predominant decrease and increase in maize and sorghum yields, respectively. The results showed that maize yields were predicted to decline by between 1% and 25% across periods. However, sorghum yields were on average predicted to increase between +5% and +21%. Overall, when adaptation is incorporated toward mid-century under RCP 8.5, yields are projected to increase for both crops. The yield projections variation between cereal crops highlights the importance of location and crop specific climate change impact assessments. Despite the uncertainties in predicting the impacts of climate change on rainfed crops, especially on cereals (maize and sorghum) which are important staple food crops in semi-arid Tanzania, the findings of this study enable policy makers to develop plans aimed at sustainable food security. In conclusion, the results demonstrate the opinion that sorghum productivity stands a better chance than

maize under prospects of negative impacts from climate change in central zone Tanzania

Key words: Climate change, Agronomic adaptation, Cereals, Simulation modelling, Policy

3.1 INTRODUCTION

Although several studies project the net effect of climate change on cereal yields to be negative in sub-Saharan Africa (SSA), the direction of yield change in any given area depends on the physiology of the crop concerned and the current climatic condition under which it is grown because different species have different base and optimum temperatures for development (Porter and Semenov 2005; Lobell *et al*., 2008; Challinor *et al.,* 2014). Rainfall projections from an assessment of 12 CMIP3 (AR4) GCMs over eastern Africa suggest an increase in rainfall by the end of the 21st Century (Shongwe *et al*., 2011; IPCC, 2013), though confounded by extreme precipitation changes (droughts and heavy rainfall) during the last 30 - 60 years (Williams and Funk, 2011; Lyon and DeWitt, 2012).

Rainfall projections for Tanzania appear consistent with those of eastern Africa, which indicate increase in annual rainfall with the ensemble range spanning changes of -4 to +30% by the 2090s (McSweeney *et al*., 2010). However, rainfall projections data from CMIP5 (Taylor *et al*., 2012) used in the Fifth Assessment Report (AR5) escalate the uncertainty in that, while overall rainfall is projected to increase by 9% for central Tanzania as observed by Wambura *et al*. (2014), analyses by Taylor *et al*. (2013) of both the Fourth Assessment Report (AR4) and AR5 multi-model ensembles attributed the projected increases to extreme monthly rainfall rather than changes to mean rainfall. Previous studies had indicated a decline in the future rainfall for central Tanzania (Paavola, 2003; Matari *et al*., 2008).

Because of the uncertainties in processes underpinning the changing climate especially on rainfall projections, more research is needed to understand the influence of the projections on crop production on local conditions. Information is required to enable an understanding of how the projected changes in climate will impact smallholder dryland farmers who need to strategically respond and adapt to the ill-effects of changing climate (Hatfield *et al*., 2011; Rurinda *et al*., 2014). It is due to this wide range of projections and the possible impacts on crop production at different scales and over different time periods that detailed studies are needed, because the underlying uncertainties exacerbate concerns about food security and impede decision making on food security policy and climate change issues (Ingram *et al*., 2008; Thornton *et al*., 2011; Yao *et al*., 2011).

Overall, although rainfall projections in eastern Africa depict a glimpse of hope regarding possible impacts on crop productivity (Doherty, 2009), other studies indicate contrasting conclusions, such as enhanced crop yields or no change in crop yields (Kurukulasuriya and Mendelsohn, 2008) and yield decreases (Thornton *et al*., 2009). Other studies in SSA show some evidence of negative climate change impact on crop yield for major staple cereal food crops like maize, sorghum and millet (Schlenker and Lobell, 2010; Knox *et al*., 2012; Berg *et al*., 2013; Zinyengere *et al*., 2013; Waha *et al*., 2013). These studies give generalized and broad conclusions about the impact of climate change which are not manifest in crop production to address increased food security concerns. In Tanzania, in particular, several studies indicate that maize production is projected to decline in the future (Mwandosya *et al*., 1998; Arndt *et al*., 2011; Rowhani *et al*., 2011; Kilembe *et al*., 2013).

The projected yields of crops under a range of climate scenarios, however, suffer from the limitations associated with the difficulty in obtaining data on local conditions or crop characteristics (Ruane *et al*., 2013; Watson and Challinor, 2013; Thornton *et al*., 2010); uncertainties in climate data (e.g. Ramirez-Villegas *et al*., 2013) and uncertainties in crop models' processes (Ainsworth *et al*., 2008). Currently, however, the weaknesses with regard to data availability and uncertainties are addressed in the methodological procedures of the Agricultural Model inter-comparison and Improvement Project (AgMIP) through aggregation of geographic data regarding the spatial distribution of climate (daily weather), topography, soils, land-use, farm-level management, socioeconomic conditions, and reported yields (Rosenzweig *et al*., 2013a, b). Moreover, the use of statistical methods to evaluate and understand uncertainty in the outputs of climate change impacts has been recognized as it enhances drawing of robust conclusions regarding model applications (Falloon *et al*., 2014).

Due to high dependence on rain-fed agriculture in Tanzania, it is clear that smallholder farmers are sensitive to possible adverse changes in climate and they are faced with the question of how to adapt to climate change. Therefore, they need information on the potential impact of climate change for the next few decades. Recent studies have established that an undertaking of climate change impact assessments at local scales is essential as it allows exploration of local agronomic management practices and their incorporation into adaptation strategies formulation (Zinyengere *et al*., 2014). In Tanzania, there is paucity of information on impacts of climate change on sorghum and maize though studies elsewhere seem to suggest that impacts on sorghum are predicted to be insignificant compared to maize. For example, according to Lobell *et al.* (2008) maize yield in Southern Africa is projected to decline by about 30% compared with a decrease of only 2% for sorghum by 2030. Other studies show that sorghum will increase by a range of 19 to 72% across eastern and southern Africa (Zinyengere *et al*., 2014; Turner and Rao, 2013). Detailed crop simulation studies at various scales are required due to spatial variability of climate especially rainfall, in order to provide relevant knowledge on impacts and for evaluating possible adaptation options under farm and policy levels (Thompson *et al.,* 2010; White *et al.,* 2011). The use of multiple-models in climate change assessment has been shown to enhance the quantification and reduction of uncertainties, as different models differ in structure and parameter values (Rötter *et al.,* 2011). A significant proportion of uncertainty in climate impact projections has been attributed to variations among crop models (Asseng *et al.,* 2013). In this study the Agricultural Production Systems sIMulator (APSIM) and Decision Support System for Agrotechnology Transfer (DSSAT) crop models were used to quantify impacts of climate variability and change on rainfed sorghum and maize productivity across five locations having contrasting soil properties and crop management practices. The specific objectives were; first, to link APSIM and DSSAT (Jones *et al*., 2003) with GCMs to simulate rainfed sorghum and maize production under the CMIP5; second, to simulate scenarios representing some agronomic strategies feasible under conditions of dryland farming to provide insight into their potential for adaptation; and third to evaluate uncertainty in climate change impacts on sorghum and maize in order to provide relevant information to policy makers and others.

3.2 Materials and Methods

3.2.1 Description of the study area

Central Tanzania (Singida and Dodoma regions) has been identified as one of livelihood zones based on FAO (Fig. 3.1). The zone is designated as "sorghum-livestock" and is most relevant to sorghum production. The central regions account for three-quarters of Tanzania's 500 000 to 800 000t annual sorghum harvests. The zone is one of the most sensitive to climate variability and change mainly owing to rainfall variability. Soils in this zone are mainly sandy and loamy of low fertility and seasonally waterlogged or flooded pockets of clays. Weather stations at five (5) locations were identified from which weather data for running crop simulation models were obtained (Table 3.1). Observed maize and sorghum yields across the zone were obtained from the Tanzania National Panel Survey (TNPS) of 2010-2011 (NBS, 2012) for the 2009/10 season.

Table 3.1: Geographical locations and rainfall characteristics of five weather stations in study area

Station	Latitude	Longitude	Altitude (m.a.s.l)	Annual rainfall (mm)	JFM (mm)	OND (mm)
Mpwapwa	-6.2	36.30	1007	584	330	183
Dodoma	-6.167	35.67	1118	567	366	107
Hombolo	-5.75	35.95	1062	627	379	180
Singida	-4.48	34.45	1377	797	419	228
Manyoni	-5.44	34.50	1245	695	385	222

m.a.s.l = metres above sea level; JFM = January February March; OND = October November December.

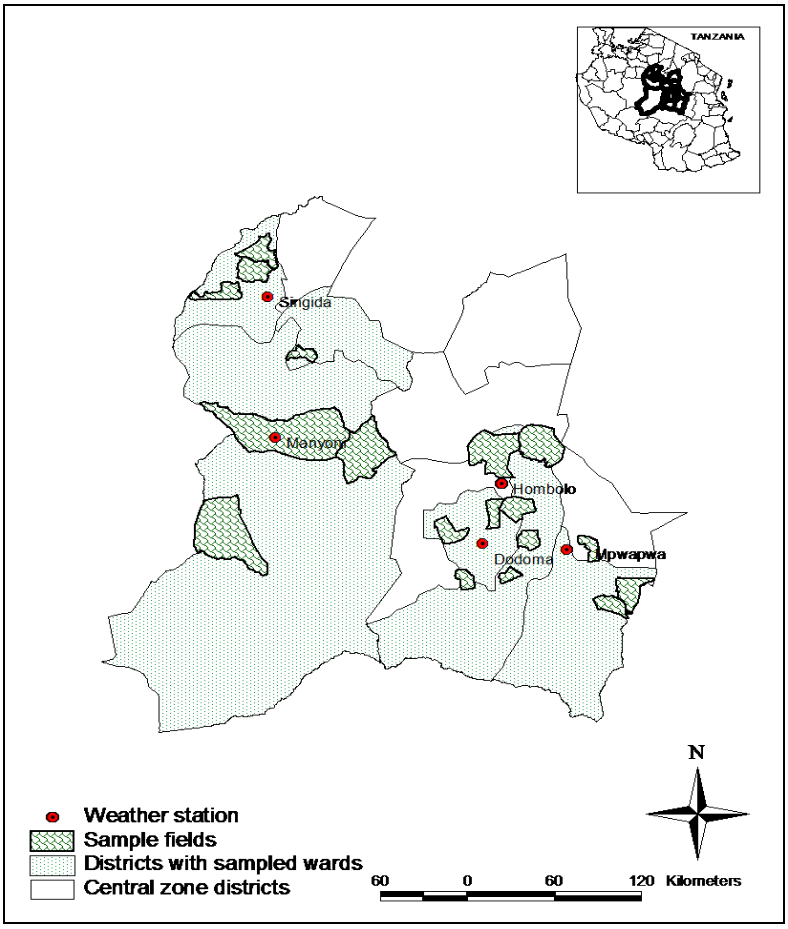


Figure 3.1: Map showing locations of fields with reported sorghum and maize yields used in model evaluation

3.2.2 Model description, calibration and evaluation

Calibration and evaluation of APSIM (Keating *et al.,* 2003) model used in this study was done based on experimental data for two growing seasons. APSIM model was evaluated for simulation of days after sowing to flowering and maturity, dry matter accumulation (biological yield) and grain yield. Genetic coefficients used by APSIM and DSSAT for sorghum are shown in Tables 3.2 and 3.3, respectively. Data for calibrating and evaluating both models for maize (Situka variety) were obtained from literature (Mourice *et al.,* 2014).

Table 3.2: Crop parameters in APSIM for three sorghum varieties

Parameter		Source	Units	Macia	Tegemeo	Pato
Thermal time accumulation	end of juvenile phase to panicle initiation	C	oC day	230	270	275
	flag stage to flowering	C	oC day	195	170	175
	flowering to start of grain filling	C	oC day	80	80	100
	flowering to maturity	C	oC day	675	760	760
	maturity to seed ripening	L	oC day	1	1	1
Photoperiod	Day length photoperiod to inhibit flowering	D	H	11.5	11.5	11.5
	Daylength photoperiod for insensitivity	D	H	13.5	13.5	13.5
	Photoperiod slope	L	oC/h	0.01	0.01	0.01
	Base temperature	L	oC day	8	8	8
	Optimum temperature	D	oC day	30	30	30
	Plant height (max)	O	mm	1290	1650	1780

C: calibrated; D: Default; L: literature; O: observed

Table 3.3: Genetic coefficients in DSSAT for three sorghum varieties

Coefficient	Definition	Macia	Tegemeo	Pato
TBASE	Base temperature below which no development occurs, °C	8.0	8.0	8.0
TOPT	Temperature at which maximum development rate occurs during vegetative stages °C	34.0	34.0	34.0
ROPT	Temperature at which maximum development rate occurs for reproductive stages °C	34.0	34.0	34.0
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.	300	440	460
P_2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.	12.5	12.5	12.5
P_2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20.	1	1	1
P5	Thermal time (degree days above a base temperature of 8°C) from beginning of grain filling (3-4 days after flowering) to physiological maturity.	520.0	650.0	650.0
G1	Scaler for relative leaf size.	15	15	15
G2	Scaler for partitioning of assimilates to the panicle (head).	6.5	6.0	6.0
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	49.0	49.0	49.0

3.2.3 Crop management and soil input data

Macia sorghum variety was chosen for subsequent analyses because it is high-yielding with early maturity, and currently highly preferred by smallholder farmers. Similarly, Situka maize variety was chosen based on its early maturity and tolerance to low nitrogen typical of the study area farm characteristics. Crop management information including planting dates, plant population, varieties used, organic and inorganic fertilizer use, intercropping and measured yields, were obtained through key informants structured interview and augmented by the information from TNPS. This information was used in the construction of a farm survey template as per AgMIP protocols (Rosenzweig *et al.,* 2013b). For the current analysis, a sample of 63 fields planted with maize and 48 fields planted with sorghum were extracted from the database (based on available reported yields), to construct farm survey template in central Tanzania. A Quick and Dirty [File Translation] User Interface (QUADUI) tool (www.agmip.org/tools) was used to translate the templates into ready model run files for the simulations.

Soil profile data used to parameterize soil modules within APSIM and DSSAT were mainly extracted from available databases e.g. Africa Soil Information Service (AfSIS) (Leenaars, 2012) and Batjes (2008), but also data from freshly dug soil profiles were used. A total of 5 soil profiles were identified to represent variable soils available within central Tanzania. Considering the variability of soils across farms, the soil profiles were deliberately subdivided to capture the soil quality based on increasing or decreasing the amount of organic carbon and amount of available water by 20% as described in the AgMIP Handbook (Rosenzweig *et al.*, 2013b). The subdivisions resulted in a total of 15 soil profiles with classes of poor, average and good quality soils. A range of analytical data for soil profiles used in the models is presented in Table 3.4.

Table 3.4: Range of soil analytical data for soil profiles used in simulations

Depth of bottom (cm)	Clay %	Silt %	Organic carbon %	pH in water	Cation Exchange Capacity (cmol/kg)	Lower Limit (LL) cm^3/cm^3	Drained upper limit (DUL)cm^3/cm^3	Saturation (SAT) cm^3/cm^3
15-25	13-55	6-20	0.35-1.26	5.4-5.9	12.8-24.2	0.077-0.355	0.128-0.441	0.349-0.499
30-45	9-59	4-16	0.24-0.76	5.1-4.8	9.0-22.1	0.057-0.375	0.108-0.454	0.358-0.517
46-80	12-59	2-18	0.1-0.6	4.5-4.8	7.5-21.8	0.102-0.386	0.216-0.456	0.324-0.508
102-115	9-55	3-6	0.04-0.49	4.0-4.8	6.8-23.0	0.150-0.305	0.362-0.441	0.376-0.529

3.2.4 Climate and data scenarios

Climate change scenarios for near-term (2010 - 2039), mid-century (2040-2069) and end-century (2071-2099) periods were generated using 20 GCMs from CMIP5 for two Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5 bias-corrected using the method of Hempel *et al.* (2013). The simulations were performed for the three climate change scenarios using data from all 20 GCMs. The climate data of five GCMs namely: CCSM4, GFDL- ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR, were separately analysed for mean changes in projected climate compared with baseline (1980 -2010). These GCMs subset were selected due to their long history of development and evaluation, a preference for higher resolution, and established performance in monsoon regions (Rosenzweig *et al,* 2013b).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models have produced corresponding emission scenarios (IPCC, 2013). The RCP8.5 is a high emissions scenario, corresponding to projections of high human population (12 billion by 2100), high rates of urbanization and limited rates of technological change, all resulting in emissions approaching 30 Gt of carbon by 2100 compared with 8Gt in 2000 (Riahi *et al.,* 2007). The RCP4.5 scenario is an intermediate mitigation scenario characterized by continuously increasing human population but at a rate lower than in the RCP8.5 scenario, intermediate levels of economic development and less rapid and more diverse technological change (Moss *et al.,* 2010).

3.2.5 Evaluation of adaptation options

According to NAPA (URT, 2007) potential adaptation measures include adjustments in management practices such as planting density, fertilizer application and planting date. Planting densities above those currently practised by smallholder dryland farmers were adopted assuming improvement in extension services and farmers' reception and adoption of the technologies. Planting density and fertilizer application were combined with two planting dates as agronomic management scenarios for each crop (Table 3.5). The selected agronomic management scenarios were based on local expert recommendations under conditions of central Tanzania and affordability by the local farmers. These were obtained from agricultural reports in respective districts. Fertilizer amounts are those recommended by experts for the low-input systems predominant in semi-arid areas of Tanzania. An early planting date (EP) corresponds to onset of rains, which have shown early trends and a late planting date (LP) serves to test the possibility of shifts of rainfall pattern in the future.

Table 3.5: Agronomic management scenarios for maize and sorghum

Crop	Management		
	Planting density (Plants/ha)	Fertilizer Application (kg N/ha)	Planting dates
Maize	33,000	40 or 60	Early: Early-mid December Late: Early-mid January
Sorghum	90,000	20 or 40	Early: Early-mid December Late: Early-mid January

3.2.6 Uncertainty and confidence assessment

Uncertainty in the projected impact of climate change on crops was assessed through two measures namely, sign of mean yield change and comparison of interannual yield variability using coefficients of variation (CV), similar to methods used by Ruiz-Ramos and Minguez (2010) and Zinyengere *et al.* (2014). The sign of mean yield change was determined for each crop, crop model, GCM and RCP. Coincidence of GCMs and crop models with the same sign of change across RCP was used to ascertain the degree of confidence in the direction of yield change. Mean CVs were compared for GCMs and RCPs, thereby identifying the sources of large uncertainty through high interannual variability.

3.3 Results and discussion

3.3.1 Climate change projections

Climate models consistently projected increased temperatures for selected weather stations in the Central zone of Tanzania. Projected temperature changes showed a mean increase in the range of 1.4–2.8 ^{o}C (Table 3.6). Dodoma station showed both the highest projected mean increase in temperature, recorded under the HADGEM2-ES (2.8 ^{o}C) and the lowest mean temperature increase with GFDL-ESM2M (1.4 ^{o}C). In contrast, the projected change in rainfall varied from one location to the other but consistently showing decline across all GCMs, except MIROC5, which showed an increase +4.5 – 7.3 % (Table 3.6). Projected mean rainfall changes were small, within a -1.7% average, although varying considerably across GCMs. While projected rainfall changes were variable and uncertain, the projected temperature changes showed strong consistency with an upward trend.

Table 3.6: Mean change in projected climate between baseline (1980-2010) and future (2040-2069) periods for RCP 8.5

Station	GCM	Temperature (^{o}C)			Rainfall (%)
		Average	Minimum	Maximum	
Dodoma	CCSM4	1.9	1.9	2.0	-2.5
	GFDL-ESM2M	1.4	1.7	1.2	-8.5
	HADGEM2-ES	2.8	2.9	2.8	-1.4
	MIROC5	2.2	2.1	2.4	7.3
	MPI-ESM-MR	2.4	2.4	2.5	-0.4
Manyoni	CCSM4	1.9	1.8	2.0	-8.9
	GFDL-ESM2M	1.8	1.8	1.7	-3.0
	HADGEM2-ES	2.7	2.6	2.8	-5.2
	MIROC5	2.3	2.1	2.4	7.0
	MPI-ESM-MR	2.3	2.1	2.4	-0.2
Singida	CCSM4	1.9	1.8	1.9	-10.3
	GFDL-ESM2M	1.8	1.8	1.7	-1.9
	HADGEM2-ES	2.7	2.6	2.8	-2.7
	MIROC5	2.3	2.1	2.4	4.5
	MPI-ESM-MR	2.6	2.7	2.4	-0.3

3.3.2 Projected crop yields

In order to use the models (APSIM and DSSAT) in projecting yields into the future they had to be calibrated using observed (survey data) yields for the 2009/2010 season as shown in Fig. 3.2. The models APSIM and DSSAT appear appropriate owing to the high R^2 values of 0.75 and 0.69 for maize and 0.82 and 0.61 for sorghum, respectively (Fig. 3.2). The calibrated models were used to simulate maize and sorghum grain yields under the three scenarios (near-term, mid-century and end-century).

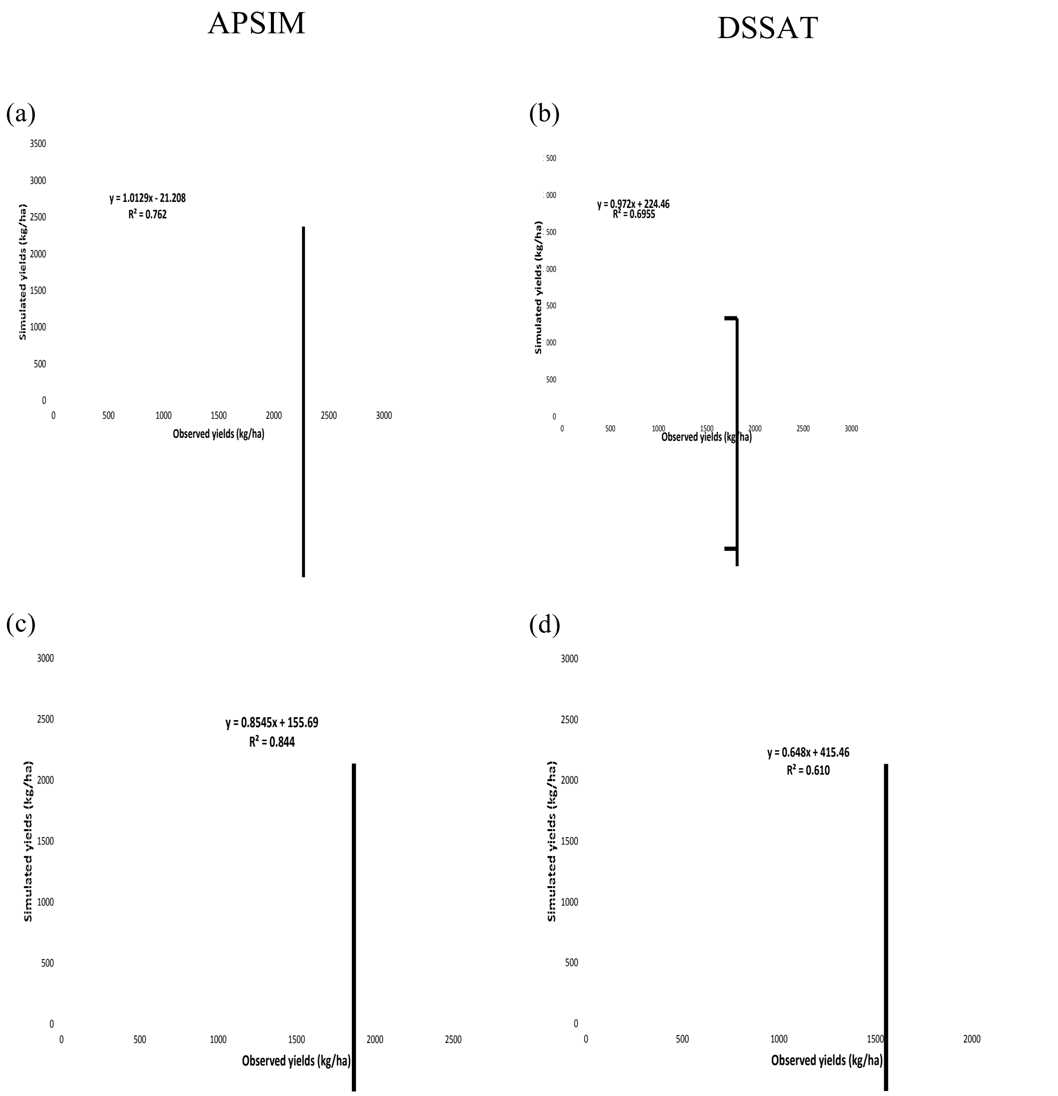


Figure 3.2: Relationship between simulated yields of maize (a and b) and sorghum (c and d) and reported yields for the season 2009-2010 (dashed line is 1:1).

Projected mean yield change showed a consistent decline for maize yields (Table 3.7). Average yield decline across all GCMs varied between 1% and 2.4% in the near term, between 3.7% and 7.1% towards mid-century and between 4.6% and 25.3% towards end of the century. In contrast, the projected sorghum yields show an increase varying between 5.4% and 6.9% in the near term, between 7.5% and 14.5% towards mid-century and between 5.7% and 20.7% towards end of the century (Table 3.8). The magnitude of yield change is higher in DSSAT than in

APSIM. This is consistent to results by Rosenzweig *et al.* (2014) who reported model agreement on direction of yield change but varying in magnitude. Sultan *et al*. (2014) observed high consistence across climate and crop models in climate and impacts projections on sorghum between the Western and Eastern parts of the Sahel. In East Africa, a study by Thornton *et al*. (2009) similarly showed yield decreases for maize over the region ranging between 1% and 15% across emissions scenarios and climate models, largely as a result of temperature increase.

Increase in sorghum yields shown by almost all GCMs under both RCPs, may be attributed to increase in temperatures and the slight changes in projected rainfall which appear to create conducive conditions for sorghum growth, being more tolerant to heat and water stress. The results are in agreement with the observations by Turner and Rao (2013) and Gwimbi *et al*. (2013), which show sorghum gaining in terms of grain yields from higher temperatures in specific regions with lower baseline temperatures (below 20^{o}C). However, Tingem *et al.* (2009) reported that for the future, little or no change or even decreases in maize and sorghum yields are projected in eight agricultural regions of Cameroon.

Projections of increased crop yields as a result of climate change have not been explored in Tanzania in particular. Recently, Kilembe *et al*. (2013) simulated yields for the climates of 2010 (baseline) and 2050 using DSSAT and showed a decrease in sorghum yields ranging from 5 % to more than 25 % of the baseline. These results suggest an overall decline in sorghum yields towards mid-century, contrary to results from the present study. This could be attributed to lack of consideration of local environments in terms of weather, soils, varieties and planting dates in the study by Kilembe *et al*. (2013). On the other hand, the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) showed significant increase in sorghum yields with climate change in Tanzania taking into account technological advancement by 2050. While results from the current study agree and/or disagree with some large scale studies, their strength emanate from the consideration of local crop specific varieties and management practices and the consideration of relevant weather information. In the central zone, the study showed that the magnitude of maize yield decline at least to mid-century is not likely to exceed 25%, results which are in agreement with Moore *et al*. (2012). In contrast, Mwandosya *et al*. (1998) projected a decline in maize yields of between 80 and 90% towards the end of the century in the same area.

Considering uncertainties introduced by the crop models' processes, it has been apparent that DSSAT being able to exhibit the effects of [CO_2] showed a relatively higher magnitude level of impacts compared with APSIM at highest projected [CO_2] i.e. 801ppm for end century RCP 8.5 (Tables 3.7 and 3.6). However, some studies have suggested that C4 plants (e.g., maize and sorghum) do not respond much to elevated levels of CO_2 (Sultan *et al*., 2013). Other studies have further shown that variable responses of the crop models to input parameters, is another source of uncertainty. For example Sadras *et al*. (2001) indicate that CERES model is more sensitive to soil water deficit whereas APSIM is relatively sensitive to physical and chemical characteristics of the soil (Wang *et al*., 2009).

Table 3.7: Percentage mean maize yield changes between baseline and three future periods for twenty Global Circulation Models (GCMs) and two Representative Concentration Pathways (RCPs): 4.5 and 8.5. (Shaded figures represent yield change for the five selected GCMs)

	DSSAT						APSIM					
	NEAR-TERM		MIDCENTURY		ENDCENTRUY		NEAR-TERM		MIDCENTURY		ENDCENTRUY	
GCMs	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
ACCESS10	-2.9	-2.7	-11.5	-12.8	-13.7	-42.7	-3.0	-4.0	-9.0	-5.8	-4.7	-20.8
BCC-CSM11	0.0	-1.1	-1.8	-6.0	-3.2	-16.0	-0.8	-1.5	-1.4	-1.4	-2.5	-8.7
BNU-ESM	-0.8	-0.8	-1.8	-4.0	-4.0	-14.6	-5.5	-4.6	-5.4	-7.0	-7.3	-12.5
CANES	-0.6	-1.7	-3.3	-5.5	-4.1	-18.0	-1.2	-1.7	-3.7	-3.7	-5.6	-12.3
CCSM4	2.0	-1.4	1.0	-2.9	-0.5	-11.9	-0.5	-1.6	-3.7	-4.0	-3.3	-10.3
CESMI	0.0	-1.6	-1.1	-3.6	-2.4	-11.9	-2.8	-3.1	-4.4	-4.3	-4.9	-8.2
CSIRO	-3.7	-2.9	-10.9	-13.7	-17.3	-36.7	-4.0	-2.8	-5.2	-5.8	-7.3	-19.3
GFDL-ESM2G	-1.7	-3.3	-10.9	0.1	0.1	-10.1	-4.6	-3.6	-3.6	-2.7	1.4	-6.5
GFDL-ESM2M	-4.5	3.7	-0.1	0.3	3.6	-0.5	-0.9	3.6	0.7	0.5	3.0	-0.1
HADGEM2-CC	-1.3	-1.1	-11.1	-21.7	-10.2	-61.9	-1.9	-1.5	-2.7	-5.2	-1.3	-21.5
HADGEM2-ES	0.0	-3.3	-7.7	-15.9	-21.1	-58.1	-0.6	-2.7	-1.7	-10.4	-8.2	-21.8
INMCM4	0.6	0.6	0.1	0.0	-1.1	-6.4	-2.2	-1.8	-3.3	-3.6	-4.2	-6.2
IPSL-LR	-1.6	-2.6	-4.5	-11.8	-10.4	-46.5	-1.7	-3.9	-0.9	-2.7	-4.1	-17.8
IPSL-MR	-1.9	-1.2	-3.6	-9.9	-11.7	-45.1	-3.1	-3.2	-1.3	-6.9	-9.6	-34.4
MIROC5	-0.1	-1.3	-3.2	-5.2	-8.5	-16.0	0.2	-2.3	-1.7	-4.1	-5.9	-6.0
MIROC-ESM	1.7	3.4	0.3	-2.3	-2.2	-19.1	-3.3	-3.4	-6.5	-8.2	-8.6	-17.1
MPI-LR	-0.3	-0.9	-2.4	-8.4	-2.6	-31.1	-2.9	-2.6	-3.9	-3.7	-2.0	-15.7
MPI-MR	0.2	-3.2	-4.1	-11.7	-4.8	-33.8	-4.4	-3.1	-5.1	-5.8	-5.1	-16.8
MRI	-5.8	-2.4	-7.5	-6.4	-5.3	-15.1	-3.6	-1.7	-9.6	-5.2	-7.4	-11.8
NORESMI	1.5	0.3	0.1	-1.1	-0.9	-9.5	-0.4	-3.2	-2.2	-2.9	-4.4	-11.1
Mean	-1.0	-1.2	-4.2	-7.1	-6.0	-25.3	-2.4	-2.4	-3.7	-4.6	-4.6	-13.9

Table 3.8: Percentage mean sorghum yield changes between baseline and three future periods for twenty Global Circulation Models (GCMs) and two Representative Concentration Pathways (RCPs): 4.5 and 8.5. (Shaded figures represent yield change for the five selected GCMs)

	DSSAT						APSIM					
	NEAR-TERM		MIDCENTURY		ENDCENTURY		NEAR-TERM		MIDCENTURY		ENDCENTURY	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
ACCESS10	-6.2	-6.0	-2.7	6.1	4.7	13.0	7.3	7.6	9.1	10.3	11.1	10.7
BCC-CSM11	6.9	8.0	12.9	15.9	12.7	10.2	7.8	7.4	9.0	9.8	7.8	8.2
BNU-ESM	3.3	3.7	7.1	12.6	10.9	19.7	4.3	4.2	4.4	5.4	4.7	6.2
CANES	4.5	6.5	9.4	13.1	10.1	20.8	4.0	5.8	4.6	3.9	2.4	5.3
CCSM4	7.3	7.1	12.8	14.6	14.3	21.4	5.7	8.3	4.6	7.6	7.9	7.9
CESMI	6.0	6.7	11.6	15.4	13.8	22.1	6.5	7.5	6.7	9.0	8.0	8.7
CSIRO	6.2	8.1	13.0	16.1	16.2	22.9	9.2	9.2	10.8	10.8	11.0	10.0
GFDL-ESM2G	4.7	7.1	11.8	14.9	15.0	20.0	6.7	9.2	8.4	6.8	10.8	7.2
GFDL-ESM2M	3.6	7.6	9.4	13.1	8.9	15.1	8.0	5.7	8.6	7.3	3.6	3.2
HADGEM2-CC	7.1	8.8	14.4	16.0	17.9	25.2	7.1	7.4	9.4	8.7	9.8	11.4
HADGEM2-ES	10.2	7.8	14.9	18.4	16.9	24.8	7.8	7.3	9.6	10.3	9.5	5.6
INMCM4	4.9	5.1	9.3	12.8	2.9	18.6	6.9	6.3	7.2	6.6	7.8	7.3
IPSL-LR	7.8	9.0	14.9	18.1	17.1	25.8	6.3	6.7	8.8	9.7	8.7	11.7
IPSL-MR	8.1	8.0	13.1	18.1	15.3	22.7	7.2	7.0	8.5	7.4	5.5	4.4
MIROC5	8.9	8.8	13.0	15.7	13.4	23.4	8.6	7.8	10.4	9.6	9.7	11.2
MIROC-ESM	4.5	4.5	9.1	9.9	9.5	22.4	3.8	1.5	1.6	1.2	-6.7	7.6
MPI-ESM-LR	7.0	5.6	10.4	15.3	14.1	21.8	6.7	6.5	6.7	8.2	0.6	7.6
MPI-ESM-MR	4.7	7.4	10.7	15.1	14.7	23.0	5.3	8.5	6.1	9.3	0.8	9.5
MRI	2.5	5.1	7.9	12.7	10.5	19.4	8.6	8.1	6.8	7.3	-0.5	6.9
NORESMI	6.6	6.0	11.1	15.2	13.4	20.7	7.4	5.9	7.7	8.4	0.8	7.2
Mean	5.4	6.2	10.7	14.5	12.6	20.7	6.8	6.9	7.5	7.9	5.7	7.9

3.3.3 Effect of adaptation options

To identify adaptation strategies for rainfed sorghum and maize in the study area, four options were evaluated under present and future climate using a subset of five GCMs. Adaptation options combine sowing dates, plant density and inorganic fertilizer applications (Table 3.5). Mean grain yields of both sorghum and maize from the two crop models under the evaluated adaptation options are shown in Fig. 3.3 and 3.4. The influence of the improved agro-systems on crop sensitivity to climate change is still a matter of debate (Turner and Rao, 2013; Sultan *et al*., 2014). While on the one hand, Turner and Rao (2013) show minimum stress from warming temperatures under the current low-input production systems (no-N fertilizer added) compared to improved systems (with adequate N fertilization), Sultan *et al*. (2014) show that increasing fertilizer inputs in the Sahel agricultural system could make it more responsive to climatic stresses and produce more negative impacts (in a relative sense, %) in crop yields under climate change. Results from both studies suggest that sorghum yields under current smallholders' low-input systems would be resilient or even increase under increasing temperatures. Moreover, the results seem to suggest that micro-dosing with Nitrogen could significantly increase yields even in the hottest and driest locations.

Fig. 3.3 shows that sorghum yields from which 20 kg N ha^{-1} of inorganic fertiliser is applied, are approximately twice as high as the yields obtained without using fertilizer and are three times higher when 40 kg N ha^{-1} of fertilizer is used. Considering variability among GCMs, GFDL-ESM and HADGEM2-ES though having contrasting characteristics (Table 3.6), produced highest mean sorghum yields. At the higher level of fertilizer application (40 kg N ha^{-1}) yield increases projected for sorghum were consistently higher under early planting than with late planting across all GCMs. Simulated sorghum yields, however, indicate that even when planting is delayed by up to one month there is no significant reduction in yields. Traore *et al*. (2014) similarly reported that a one month delay in planting sorghum and maize did not significantly affect the final yields.

Results of simulated maize yields under evaluated adaptation options are shown in Fig. 3.4. Even though rain-fed maize production is determined by the adequacy, reliability and timeliness of rainfall, simulated grain yields were increased with inorganic fertilizer application amount. However, farmers are averse to taking risks and therefore, not ready to invest in inputs and improvements if they are not sure of securing good yields in a particular season, as a result low levels of productivity persist (Bezabih and Di Falco, 2012). Application of fertilizers will become more critical if farmers are to reduce their vulnerability to the impacts of climate change. Besides application of fertilizers, adjustments in planting densities and sowing dates will also be of major importance.

Unlike sorghum, there is an appreciable difference in maize yields among the GCMs with GFDL-ESM giving the highest and HADGEM2-ES giving the lowest yield. This could be due to the effect of projected increase in temperature between the two GCMs (Table 3.6) where GFDL-ESM projects the lowest increase in average temperature by mid-century whereas the converse is true for HADGEM2-ES. Studies have shown that increased temperatures and change in rainfall patterns will affect major staple cereal food crops such as maize, sorghum and millets because of possible yield decline in future (Zinyengere *et al*., 2013; Lobell *et al*., 2011). For example, analyses by Lobell *et al*. (2011) show that each degree day spent above 30°C reduces maize grain yield by 1% under optimal rain-fed conditions, and by 1.7% under drought conditions in Africa.

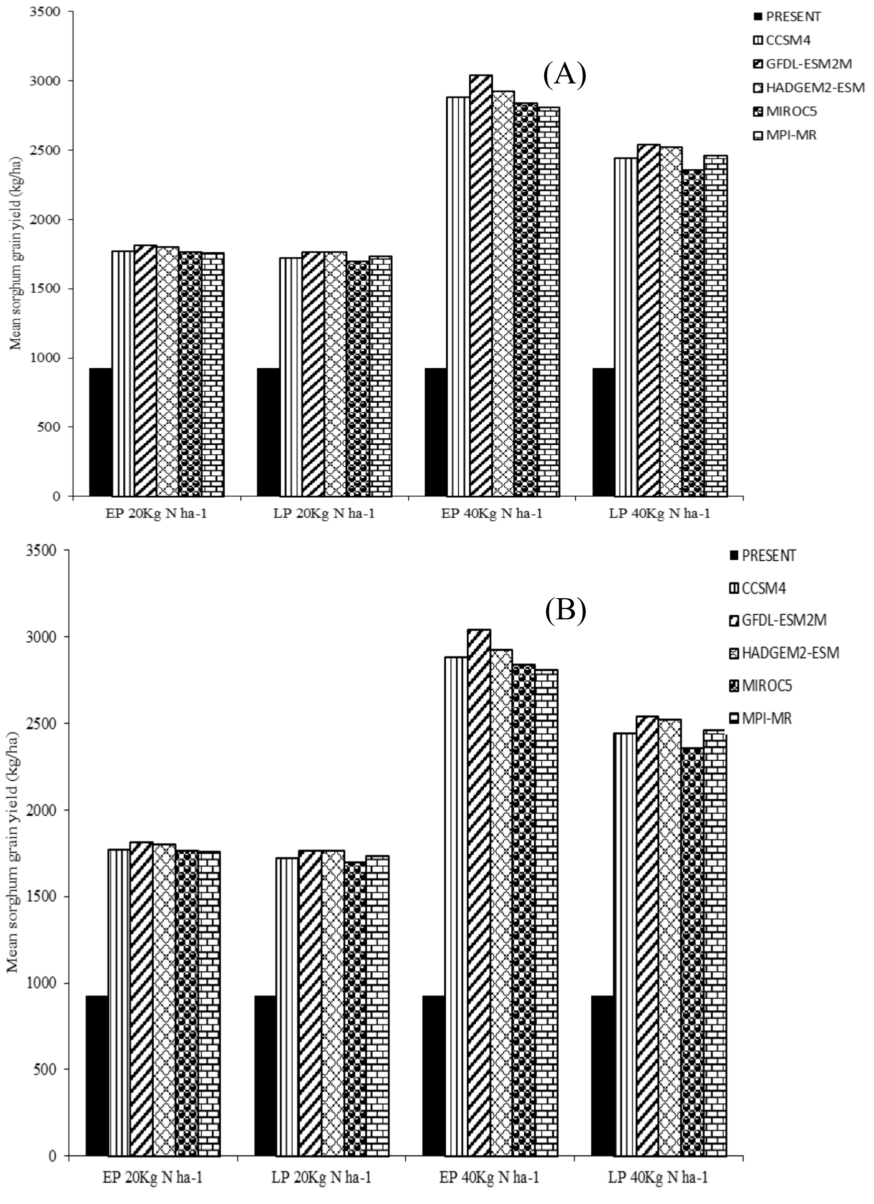


Figure 3.3: Mean simulated sorghum grain yields under different adaptation options for present (baseline) and mid-century (RCP8.5) using GCMs with APSIM (A) and DSSAT (B). EP = Early planting; LP = Late planting

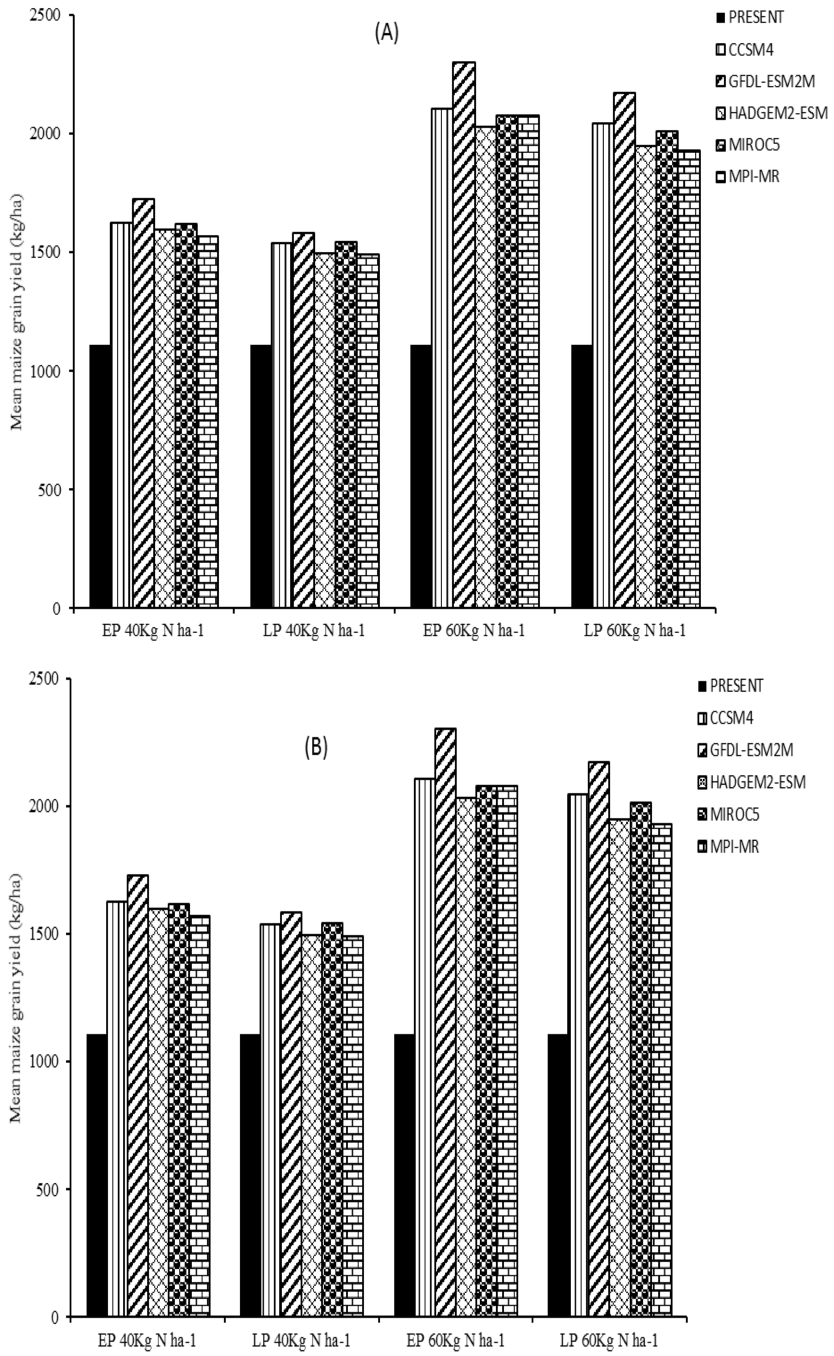


Figure 3.4: Mean of simulated maize grain yields under different adaptation options for present (baseline) and mid-century (RCP8.5) using GCMs with APSIM (A) and DSSAT (B). EP = Early planting; LP = Late planting

3.3.4 Uncertainty on climate change impact and adaptation options

According to the simulation results from the five GCMs, a clear trend that is consistent across crop models and RCPs has been established in as far as yield change is concerned (Tables 3.7 and 3.8). Interannual variability of yield under both crop models ranged from a mean CV of 37% to 55% for sorghum and 56% to 70% for maize (Fig. 3.5). Mean CVs were higher for APSIM than for DSSAT and also higher for maize than for sorghum. The results confirm the uncertainty brought about by the crop models due to differences in parameters (Asseng *et al*., 2013). The higher range of predictions for maize across GCMs, reflects the uncertainty of climate prediction impacts using GCMs. Similar results were obtained by Moore *et al*. (2012) who reported between 20% and 30% decrease in maize yields toward mid-century in Morogoro. They attributed the uncertainty to combined effects of greenhouse gas emissions and land cover land use change (LCLUC). Similar results were obtained in Zimbabwe where a GCM and CERES-maize showed that maize yields would decrease by approximately 11 – 17%, under irrigated and non-irrigated conditions (Stige *et al*., 2006).

The coefficient of variation (CV) from simulations incorporating agronomic adaptation options is illustrated in Fig. 3.6. While uncertainty remains a factor, a clear trend was established in that yield variability was least influenced by GCMs as shown by the limited differences in CVs, except for HADGEM-ES under DSSAT and early planting scenario which showed increased variability over and above other GCMs (Fig. 3.6d). To a large extent, yield variation appears to have been driven by agronomic adaptation options (Fig. 3.6). Agronomic adaptation strategies influenced uncertainty considerably (low CVs of less than 18%) as shown in Fig. 3.6d) compared with high CVs of up to 59% when simulations were run under current agronomic management practices i.e. mainly without fertilizer application. The results are in agreement with Walker and Schulze (2008) who reported reduced variability for treatments using inorganic fertiliser under all the future climate scenarios modelled compared with the CV of maize yields under previous climate conditions.

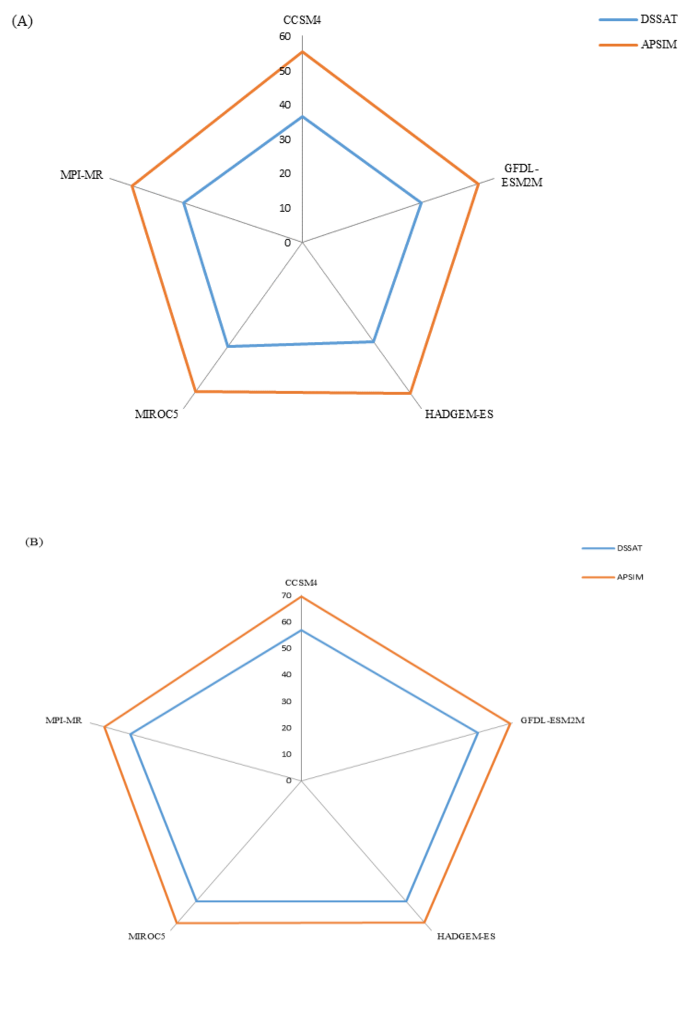
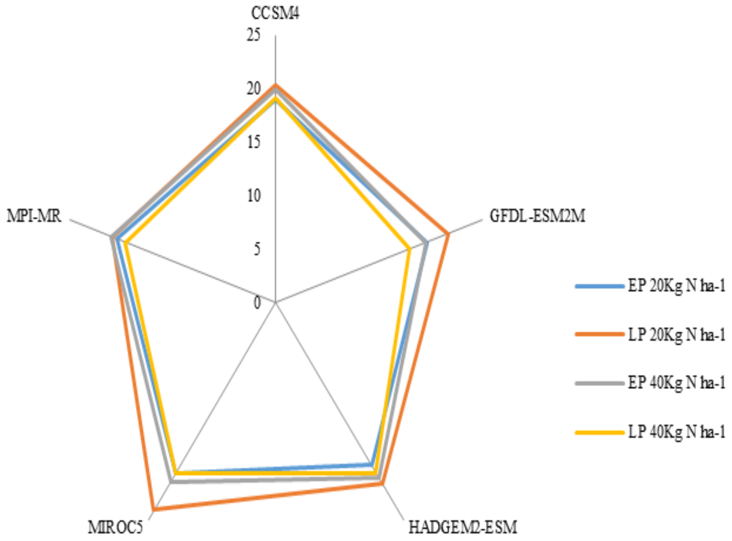
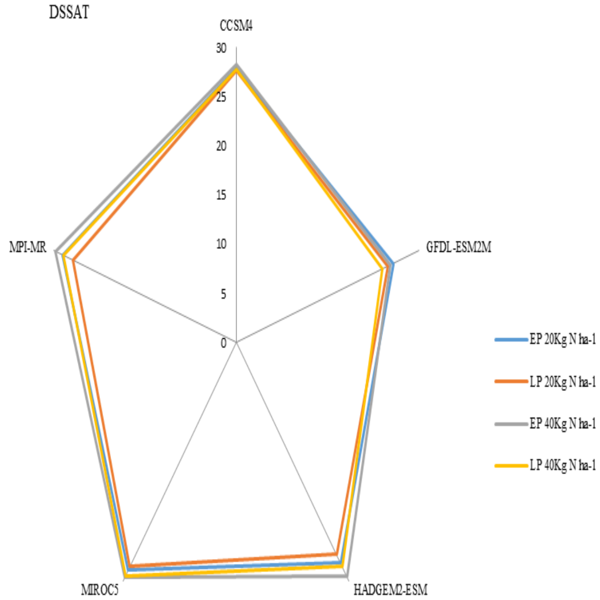


Figure 3.5: Mean percentage values of coefficient of variation for Sorghum (A) and maize (B) clustered by GCMs

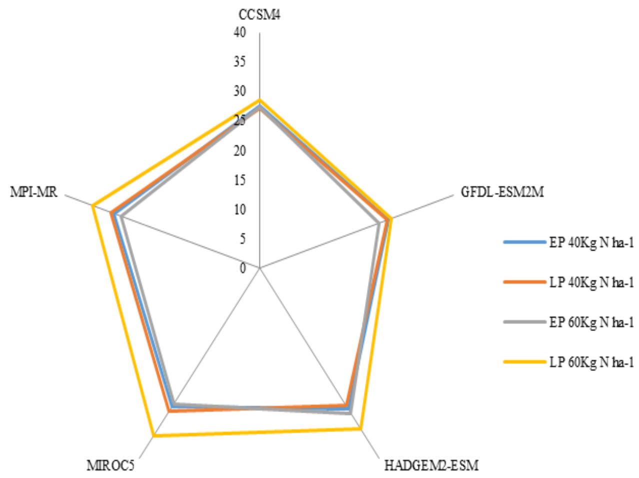
(A) APSIM



(B) DSSAT



(C) APSIM



(D) DSSAT

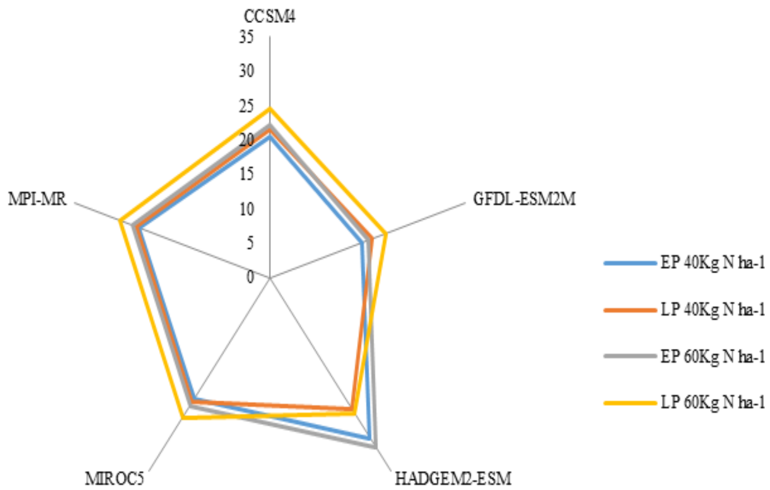


Figure 3.6: Mean percentage values of coefficient of variation for Sorghum (A and B) and maize (C and D) yields with respect to adaptation options clustered by GCMs

3.2 Conclusions

Results from this study demonstrate how crop simulation models coupled with GCMs could play a role in policy decisions with respect to climate change considerations. It has been shown that sorghum yields will consistently increase over different time periods with up to 25% increase towards the end of the century. On the other hand, overall maize yields, by contrast, have been projected to decline. Basic agronomic adaptation options such as fertilizer applications, appropriate planting density and planting dates appear to be ideal for future climate uncertainties. This has a bearing on agricultural plans and policies which may need to be reoriented for enhanced crop productivity.

Despite the uncertainty in crop models and GCMs, the results enhance people's understanding of current climate variability as well as the anticipated climate change which is appropriate for informed agricultural management decisions. Furthermore, the results accentuate the uncertainty that comes from using different models in climate change assessments. All in all the study has contributed to a better understanding of large-area modelling because existing large-area crop models do not currently simulate the non-climatic (e.g. local cultivars and crop management practices) determinants of crop yield; factors which also need considerations if useful insights are to be provided for future decision making in a rapidly changing climate.

3.3 REFERENCES

Ainsworth, E. A., Leaky, A. D. B, Ort, D. R. and Long, S. P. (2008). FACE-ing the facts: inconsistencies and interdependence among field, chamber and modelling studies of elevated [CO2] impacts on crop yield and food supply. *New Phytology* 179: 5 – 9.

Arndt, C., Farmer, W., Strzepek, K. and Thurlow, J. (2011). Climate change, agriculture and food security in Tanzania. Working Paper No. 2011/52 United Nations University-World Institute for Economic Development Research (UNU-WIDER). 26 pp.

Asseng, S., Ewert, F. and Rosenzweig, C. *et al*. (2013). Uncertainty in simulating wheat yields under climate change. *Nature Climate Change* 3: 827 - 832.

Batjes, N. H. (2008). ISRIC-WISE Harmonized Global Soil Profile Dataset (Ver. 3.1.). Report 2008/02, ISRIC-World Soil Information, Wageningen (with dataset). [http://www.isric.org/isric/webdocs/Docs/ISRIC Report 2008 02.pdf]. Site visited on 12/03/2013.

Berg, A., de Noblet-Ducoudr´e, N., Sultan, B., Lengaigne, N. and Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology* 170: 89 -102.

Bezabih, M. and Di Falco, S. (2012). Rainfall variability and food crop portfolio choice: evidence from Ethiopia. *Food Security* 4(4): 557 – 567.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R. and Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change* 4: 287 - 291.

Doherty, R., Sitch, S., Smith, B., Lewis, S. and Thornton, P. (2009). Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology* 10: 365 – 386.

Falloon, P., Challinor, A., Dessai, S., Hoang, L., Johnson, J. and Koehler, A. (2014). Ensembles and uncertainty in climate change impacts. *Frontiers in Environmental Science* 2 (33): 1 - 7.

Gwimbi, P., Thomas, T. S. and Hachigonta, S. (2013). Assessing the vulnerability of agriculture to climate change in Lesotho. *In: Southern African Agriculture and Climate Change: A Comprehensive Analysis.* (*Edited by Hachigonta, S. et al.*), International Food Policy Research Institute, Washington, DC. pp. 287 – 299.

Hatfield, L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., Thomson, A. M. and Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. *Agronomy Journal* 103: 351 - 370.

Hempel, S., Frieler, K., Warszawski, L., Shewe, J. and Piontek, F. (2013). A trend-reserving bias correction – the ISI-MIP approach. *Earth Systems Dynamics* 4: 219 – 236.

Ingram, J. S. I., Gregory, P. J. and Izac, A. M. (2008). The role of agronomic research in climate change and food security policy. *Agriculture Ecosystems and Environment* 126: 1 - 12.

IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D. and Plattner, G.-K., Tignor, M. S. K., Allen, J., Boschung, A., Nauels, Y., Xia, V. Bex and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 764pp.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J. and Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy* 18: 235 – 265.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, .I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M. and Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18: 267 – 288.

Kilembe, C., Thomas, T.S., Waithaka, M., Kyotalimye, M. and Tumbo, S. (2013). *Tanzania*. In: *East African Agriculture and Climate Change: A Comprehensive Analysis. (Edited by Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M.).* IFPRI, Washington, DC. pp. 313 - 343.

Knox, J., Hess, T., Daccache, A. and Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters* 7: 034032, 8pp.

Kurukulasuriya, P. and Mendelsohn, R. (2008). *How will climate change shift agro-ecological zones and impact African agriculture?* A report submitted to the World Bank. 30pp.

Leenaars, J. G. B. (2012). Africa Soil Profiles Database Version 1.0. A compilation of georeferenced and standardized legacy soil profile data for Sub Saharan Africa (with dataset). ISRIC report 2012/03. Africa Soil Information Service (AfSIS) project and ISRIC-World Soil Information, Wageningen, the Netherlands. 354pp.

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P. and Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science* 319: 607 - 610.

Lobell, D. B., Bänziger, M., Magorokosho, C. and Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change* 1: 42 - 45.

Lyon, B. and DeWitt, D. G. (2012). A recent and abrupt decline in the East African long rains. *Geophysical Research Letters*. 39 (2): 33 – 40.

Matari, E. E., Chang'a, L. B., Chikojo, G. E. and Hyera, T. (2008). Climate change scenarios development for second national communication, Tanzania. *TMA Research Journal* 1: 8 - 18.

McSweeney, C., New, M. and Lozano, G. (2010). The UNDP Climate change country profiles, Tanzania. Improving the accessibility of observed and projected climate information for studies of climate change in developing countries. [http://country-profiles.geog.ox.ac.uk]. Site visited on 25/6/2013.

Moore, N., Alagarswamy, G., Pijanowski, B., Thornton, P., Lofgren, B., Olson, J., Andresen, J., Yanda, P. and Qi, J. (2012). East African food security as influenced by future climate change and land use change at local to regional scales. *Climatic Change* 110: 823 – 844.

Moss, R. H., Edmonds, J. A., Hibbard, K.A. et al., (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463: 747 - 756.

Mourice, S. K., Rweyemamu, C. L., Tumbo, S. D. and Amuri, N. (2014). *Maize Cultivar Specific Parameters for Decision Support System for Agrotechnology Transfer (DSSAT) Application in Tanzania*. *American Journal of Plant Sciences* 5: 821 - 833.

Mwandosya, M. J., Nyenzi, B. S. and Luhanga, M. L. (1998). The Assessment of Vulnerability and Adaptation to Climate Change Impacts in Tanzania. Dar-es-Salaam, Tanzania: Centre for Energy, Environ. Sci. Technol. CEEST). 159pp.

NBS (2012). *Tanzania National Panel Survey Report Wave 2, 2010 -2011, Living Standards Measurements Survey*, National Bureau of Statistics, Dar-es-Salaam, Tanzania. 273pp.

Paavola, J. (2003). "Vulnerability to Climate Change in Tanzania: Sources, Substance and Solutions, A paper presented at the inaugural workshop of Southern Africa Vulnerability Initiative (SAVI) in Maputo, Mozambique. 83pp.

Porter, J. R. and Semenov, M. A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society* B 360: 2021 – 2025.

Ramirez-Villegas, J., Challinor, A, Thornton, P. and Jarvis, A. (2013). Implications of regional improvement in global climate models for agricultural impact research. *Environmental Research Letters* 8 (12): 034052, 8pp.

Riahi, K., Grübler, A. and Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change* 74: 887 - 935.

Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G. and Winter, J. M. (2013a). The agricultural model intercomparison and improvement project (AgMIP). Protocols and pilot studies. *Agricultural and Forest Meteorology* 170: 166 - 182.

Rosenzweig, C., Jones, J., Hatfield, J., Antle, J., Ruane, A., Boote, K., Thorburn, P., Valdivia, R., Porter, C., Janssen, S. and Mutter, C. (2013b). AgMIP Guide for Regional Integrated Assessments: Handbook of Methods and Procedures Version 5.0. 21pp.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müllere, C., Arneth, A., Boote, K. J., Folbert, C., Glotteri, M., Khabarov, N., Neumann, K., Pionteke, F., Pugh T. A. M., Schmid, E., Stehfest, E., Yangh, H. and Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model inter-comparison. *Proceeding of National Academy of Sciences.* 12pp.

Rötter, R. P., Carter, T. R., Olesen, J. E. and Porter, J. R. (2011). Crop-climate models need an overhaul. *Nature Climate Change* 1: 175 - 177

Rowhani, P., Lobell, D. B., Linderman, M. and Ramankutty, N. (2011). Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology* 151: 449 – 460.

Ruane, A. C., Cecil, L. D., Horton, R. M., Gordon, R., McCollum, R., Brown, D., Killough, B., Goldberg, R., Greeley, A. P. and Rosenzweig, C. (2013). Climate change impact uncertainties for maize in Panama: farm information, climate projections, and yield sensitivities. *Agricultural and Forest Meteorology* 170: 132 - 145.

Ruiz-Ramos, M. and Minguez, M. I. (2010). Evaluating uncertainty in climate change impacts on crop productivity in the Iberian Peninsula. *Climate Research* 44: 69 – 82.

Rurinda, J., Mapfumo, P., van Wijk, M. T., Mtambanengwe, F., Rufino, M. C., Chikowo, R. and Giller, K. E. (2014). Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *European Journal of Agronomy* 55: 29 - 41.

Sadras, V. O. and Calviño, P. A. (2001). Quantification of grain yield response to soil depth in soybean, maize, sunflower, and wheat. *Agronomy Journal* 82: 577 – 583.

Schlenker, W. and Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* 5(1): 014010, 8pp.

Shongwe, M. E., van Oldenborgh, G. J., van den Hurk, B. and van Aalst, M. (2011). Projected changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa. *Journal of Climate* 24(14): 3718 - 3733.

Stige, L. C., Stave, J., Chan, K. S., Ciannelli, L., Pretorelli, N., Glantz, M., Herren, H. R., and Stenseth, N. C. (2006). The effect of climate variation on agro-pastoral production in Africa. *Proceedings of the National Academy of Science. USA* 103: 3049 - 3053.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S. and Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*. 8(2):014040, 8pp.

Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G. L., McLean, G and Lobell, D. B. (2014). Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters* 9(1):032060, 8pp

Taylor, K. E., Stouffer, R. J. and Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of American Meteorological Society* 93: 485 – 98.

Taylor, R. G., Todd, M. C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. and MacDonald, A. M. (2013). Evidence of the dependence of groundwater reso urces on extreme rainfall in East Africa. *Nature Climate Change* 3: 374 - 378.

Thompson, H. E., Berrang-Ford, L. and. Ford, J. D. (2010). Climate change and food security in sub- Saharan Africa: A systematic literature review. *Sustainability* 2: 2719 - 2733.

Thornton, P. K., Jones, P. G., Alagarswamy, A. and Andresen, J. (2009). Spatial variation of crop yield responses to climate change in East Africa. *Global Environmental Change* 19: 54 - 65.

Thornton, P. K., Jones, P. G., Alagarswamy, G., Andresen, J. and Herrero, M. (2010). Adapting to climate change: Agricultural system and household impacts in East Africa. *Agricultural Systems* 103: 73 - 82.

Thornton, P. K., Jones, P. G., Ericksen, P. J. and Challinor, A. J. (2011). Agriculture and food systems in sub- Saharan Africa in a 4 ^{o}C + world. *Philosophical Transactions of the Royal Society* 369: 117 – 136.

Tingem, M., Rivington, M. and Bellocchi, G. (2009). Adaptation assessment for crop production in response to climate change in Cameroon. *Agronomy Sustainable Development* 29: 247 - 256.

Traore, B., van Wijk, M. T., Descheemaeker, K., Corbeels, M., Rufino, M. C. and Giller, K. E. (2014). Evaluation of climate adaptation options for Sudano-Sahelian cropping systems. *Field Crops Research* 156: 63 - 75.

Turner, N. C. and Rao, K. P. C. (2013). Simulation analysis of factors affecting sorghum yield at selected sites in eastern and southern Africa, with emphasis on increasing temperatures. *Agricultural Systems* 121: 53 – 62.

URT (2007). United Republic of Tanzania, "National Adaptation Programme of Action (NAPA)" Division of Environment, Vice President's Office, Dar es Salaam. 61pp.

Waha, K., Müller, C. and Rolinski, C. (2013). Separate and combined effects of temperature and precipitation change on maize yields in sub-Saharan Africa for mid- to late-21st century. *Global Planetary Change* 106: 1 – 12.

Walker, N. J. and Schulze, R.E. (2008). An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystems in Kwazulu-Natal, South Africa. *Physics and Chemistry of the Earth* 31: 995 – 1002.

Wambura, F., Ngongolo, H., Mlonganile, P., Sangalugembe, C. and Tumbo, S. (2014). CMIP5 climate change projections for Tanzania. A paper presented at the International Conference on Reducing Climate Change Challenges through Forestry and other Land Use practices 1st – 3rd April 2014, Nashera Hotel, Morogoro, Tanzania. 14pp.

Wang, J., Wang, E. L., Luo, Q. Y. and Kirby, M. (2009). Modelling the sensitivity of wheat growth and water balance to climate change in Southeast Australia. *Climatic Change* 96: 79 – 96.

Watson, J. and Challinor, A. (2013). The relative importance of rainfall, temperature and yield data for a regional-scale crop model. *Agriculture and Forest Meteorology* 170: 47 – 57.

White, J. W., Hoogenboom, G., Kimball, B. A. and Wall, G. W. (2011). Methodolog ies for simulating impacts of climate change on crop production. *Field Crops Research* 124: 357 - 368.

Williams, A. P. and Funk, C. (2011). A westward extension of the warm pool leads to a west-ward extension of the Walker circulation, drying eastern Africa. *Climate Dynamics* 37: 2417 – 2435.

Yao, F. M., Qin, P. C., Zhang, J. H., Lin, E and Boken, V. (2011). Uncertainties in assessing the effect of climate change on agriculture using model simulation and uncertainty processing methods. *Chinese Science Bulletin* 56: 729 – 737.

Zinyengere, N., Crespo, O. and Hachigonta, S. (2013). Crop response to climate change in southern Africa: A comprehensive review. *Global and Planetary Change* 111: 118 -126.

Zinyengere, N., Crespo, O., Hachigonta, S. and Tadross, M. (2014). Local impacts of climate change and agronomic practices on dryland crops in Southern Africa. *Agriculture Ecosystems and Environment* 197: 1 – 10.

CHAPTER FOUR

4.0 DETERMINANTS OF FARM LEVEL DECISIONS REGARDING CEREAL CROPS AND VARIETIES IN SEMI-ARID CENTRAL TANZANIA

ABSTRACT

A study was conducted to assess the potential and constraints of increased sorghum production to enhance food security and livelihoods in central Tanzania. Sorghum and pearl millet are well adapted dryland cereals and show a high potential to contribute to local food security, but adoption is limited. The study employed a structured questionnaire survey as the main data collection method. Data analysis involved the use of Multinomial logit model (MNL) in combination with other descriptive statistics to determine the socio-economic and agro ecological variables influencing crop and variety choices and preferences. Empirical results revealed that age of the household head, farming experience, soil types and access to weather information significantly influence choices of cereal crops among sorghum, pearl millet and maize. On the same token, age, farming experience, farmer-extension contact and access to weather information were important factors on the choice of sorghum varieties viz. local landraces versus improved. Farmers' perception results show that harvest and post-harvest processes, consumer tastes and preferences, and market access and prices strongly influence farmers' decisions to grow sorghum. In conclusion the results show that although sorghum and pearl millet contribute to the food supply, perceptions, agro-ecological variables and socio-economic factors collectively constrain the realization of their potential in minimizing household food insecurity.

Key words: Drought tolerant cereals, agro-ecological, perception, multinomial logit, food security, livelihoods

4.1 INTRODUCTION

It is estimated that in sub-Saharan Africa, sorghum and pearl millets account for 8% of the cultivable land area which support about 9% of the population mainly in the agro-pastoral millet/sorghum farming system (Dixon *et al*., 2001). There is perpetual food-insecurity among the people living in central regions of Tanzania due to existence of unfavourable agricultural conditions. In these regions, promotion of adoption of drought tolerant crops like cassava, millet or sorghum, despite their low market value, increase the potential to ensure households food sufficiency especially when crops like maize fail (Monyo *et al*., 2002). With the help from donors, Tanzania government through the Agricultural Sector Development Strategy (ASDS) (URT, 2001) and the recent initiative *Kilimo Kwanza* (of 2010), is promoting the use of small grain cereals to fight food insecurity in semi-arid areas of Tanzania. As a result of concerted efforts of government and donors, several new improved varieties of sorghum and millets have been released and are being disseminated to farmers (SADC/ICRISAT SMIP, 1998). Despite these efforts, adoption of these improved crop varieties by rural farmers, which would lead to increased crop production, is still limited.

Previous studies conducted to identify factors determining adoption of cereal crops in Tanzania, mainly maize (Kaliba *et al*., 2000) and sorghum (Mafuru *et al*., 2007; Bucheyeki *et al*., 2010) focused more on socio-economic variables than on agro-ecological and farmers' perceptions. Since the studies were conducted on a limited area it is not possible to apply them to other regions because they did not consider the role of all important indicators for agricultural water management. Although applied at continental scales, Valipour (2014a, b, 2015a) underscores the importance of inclusion of socio-economic indices in water management aspects for food security. Moreover, Kafle (2010) suggests the consideration of all factors as they are equally important in the understanding of the determinants of adoption of agricultural innovations. Though it is strongly argued that farmers in semi-arid areas where sorghum and pearl millet are produced are reluctant to invest in new crop management practices such as improved varieties and manure application, reasons for the hesitancies remain unclear. Natural resource management practices that improve soil fertility do exist, but farmer adoption of the practices on sorghum and pearl millet is continually declining (Ley *et al.*, 2001). Some studies cite high production risks, limited incentives to increase productivity and limited access to markets for these small grains as the most important factors which deter smallholder farmers to adopt promising agricultural innovations (Rohrbach and Kiriwaggulu, 2007). Moreover, an over-reliance on a cultivar-alone strategy, such as the introduction of improved sorghum or millet varieties, seems to give limited gains (Ahmed *et al.*, 2000), indicating that other driving factors may have a contributing role in determining productivity of cereals.

Recent analyses have recommended some agricultural innovations to improve productivity of cereals, for example, promotion of adoption of conservation agriculture technologies without considering whether they give immediate economic returns (Kahimba *et al.*, 2014). Studies at the continental scale indicate that Africa needs governments' policy to provide an enabling environment for smallholder farmers to use irrigation systems and raise cropping intensity in the irrigated area in the future (Valipour, 2014c). Moreover, analyses by Valipour (2015b, c) and Valipour *et al.* (2015) using information from Food and Agriculture Organization

(FAO) database show that appropriate policies are required which ensure accurate scheduling of water resources and designing of suitable cropping patterns for the irrigation systems to attain sustainable agriculture in future. Westengen and Brysting (2014) recommends maintenance of cereal crop and variety diversity through growing local landraces alongside improved varieties of maize and sorghum as a livelihood response strategy of crop adaptation to not only climatic stresses but also other abiotic stresses (e.g. pests and diseases) in central Tanzania. Though some empirical studies have attempted to analyse the impact of climate and other factors influencing the choice of crop and cropping systems (Below *et al*., 2011; Waha *et al*., 2013), there is paucity in knowledge of determinants of farmers' choice of cereal crops and crop varieties encompassing agro-ecological and farmers' perception in the central semi-arid areas of Tanzania. A deeper analysis of the agro-ecological, farmers' perceptions and socio-economic factors determining production in the sorghum and pearl millet-based farming system is thus needed to elucidate their influence on the adaptive capacity of smallholder farmers to multifaceted challenges predominant in the system.

We analyse factors that determine cereal crops and crop varieties choices among farming households, with the goal of understanding farmers' perceptions, and the socio-economic and agro-ecological factors influencing of the decision to produce sorghum or another cereal in a given cropping season and the choice between local landraces and improved varieties. Policy makers would be provided with additional insight into the relationship between sorghum production and the changing driving factors. We describe current yields, patterns and trends of sorghum production in relation to maize and pearl millet and we identify the determinant factors that impel patterns and trends in sorghum production, in relation to maize and millet production.

4.2 Methodology

4.2.1 Study area

The central zone (Dodoma and Singida) is located between latitudes 6^0 and $06^0$08’ S and longitudes $34^0$30’ and 35^0 45’E. The study was conducted in two villages of Bahi District, namely Makanda and Lamaiti, and two villages of Chamwino District, namely Mlowa Bwawani and Wiliko, Dodoma Region. Additionally, two villages of Iramba District, namely Kisiriri and Kisana and two villages of Singida rural District that is Ikhanoda and Ngamu, Singida region were involved. Both Regions are situated in the semi-arid zone of central Tanzania and have a dry savannah type of climate, which is characterized by long dry season, unimodal and erratic rainfall that falls between November/December and April. Dodoma Region has an annual average rainfall of about 500 to 700 mm and annual average temperature of about 22.6^0C. Singida region has an annual average rainfall of about 500 to 800 mm and annual average temperature of about 20.4^0C. The zone is one of the most sensitive to climate variability and change, but it accounts for three-quarters of Tanzania’s 500 000 to 800 000 tonnes of annual sorghum harvest. Soils in this zone are mainly sandy and loamy of low fertility and seasonally waterlogged or flooded pockets of clays. The big proportion of central Tanzania is covered by three major soils namely Cambisols, Luvisols and Vertisols (Fig. 4.3).

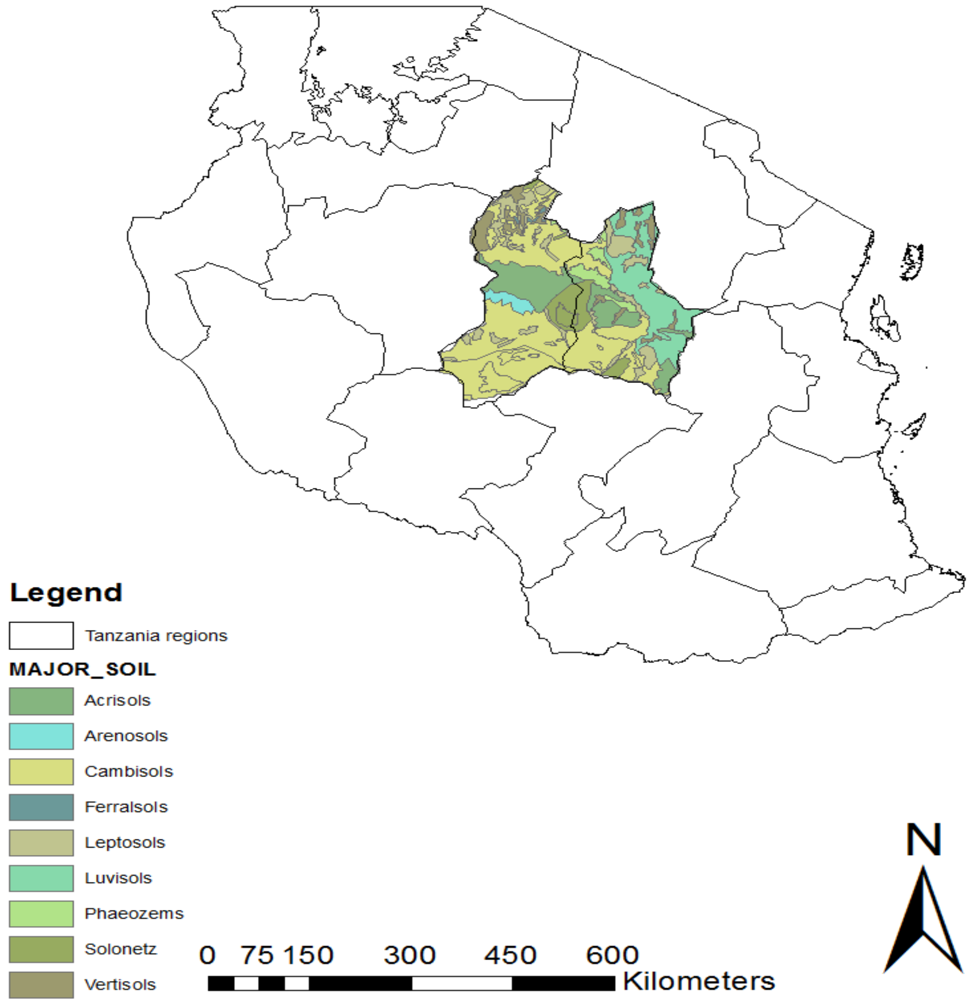


Figure 4.1 Map showing dominant soils in central regions of Tanzania

4.2.2 Research design and methods of data collection

In the study both primary and secondary data were used. The study sample was obtained by using simple random sampling technique from a sampling frame of farming households who were dealing with cereal crops production and livestock keeping. A structured questionnaire was used to gather both qualitative and quantitative information covering aspects about patterns and trends, influence of biophysical (soil) and socio-economic factors on cereal crops production, discrete choices of cereals and ultimately the choices of sorghum varieties grown by farming households. The questionnaire was administered to a sample of 240 respondents. Secondary data were gathered from various reports relevant to the study and the web.

4.2.3 Data analysis

Likert type plot (diverging stacked bar chart) on socio-economic constraints on sorghum was generated from R using HH package (Heiberger and Robbins, 2014). The Multinomial Logit (MNL) model was used to analyse the factors influencing choice of growing one cereal crop among smallholder farmers in the two regions viz. Dodoma and Singida. The MNL parameter estimates are obtained using maximum likelihood estimation method given in MLOGIT routine for STATA version 11. Explanatory variables used to describe the choices of crop and crop varieties are shown in Table 4.1. The size of the plots (acreage) allocated for each cereal by the farmers during the season of 2011/12 was used as a proxy for the preference of that particular farmer to choose a given cereal i.e. the higher the acreage the higher the preference. The 2011/12 season was chosen between the two previous seasons due to its relatively good rains in the study area compared to 2012/13 season. The MNL model was preferred because it permits the analysis of decisions across more than two categories in the dependent variable; hence it becomes possible to determine choice probabilities for the different cereals.

Table 4.1: Variables used in the MNL model and their expected signs

Variable name	Variable description and measurement	Variable type	Expected sign
CRPTYPE	Choice of a crop relative to other crops		
EDUC	Years of school completed by household head (number)	continuous	+/-
AGE	Age of household head (years)	continuous	+/-
FEXPERIENCE	Farming experience of household head (years)	continuous	+/-
HSIZE	Household size (numbers)	discrete	+/-
PLOTSIZE	Size of cultivated land in hectares	continuous	+/-
SLTYPE1	Sandy reddish fine soils (*Isang'ha)*	continuous	+/-
SLTYPE2	Red deep heavy soils (*Ng'uluhwi)*	continuous	+/-
SLTYPE3	Whitish/Reddish soils (*Tifutifu)*	continuous	+/-
SLTYPE4	Red sandy soils (*Sanghamanya)*	continuous	+/-
SLTYPE5	Sandy soils along the sandy rivers *(Msawawa)*	continuous	+/-
SLTYPE6	Black or grey alluvial cracking soils (*Mbuga)*	continuous	+/-
DISMRKT	Distance to the nearest market (km)	continuous	
EXTNCNT	Farmer received extension contact in 2011/12 (numbers)	discrete	+/-
SUPPORT	Farmer obtained support (seed or fertilizer) in 2011/12 (dummy)	continuous	+/-
CLIMINFO	Household head has access to weather information (dummy)	dummy	+/-
TRAINING	Household head participate in training (dummy)	dummy	+/-

To describe the MNL model, let y denote a random variable taking on the values {1,2….j} for choices j, a positive integer, and let *x* denote a set of conditioning variables. In the first case, y represents the cereal crop chosen by any farming household in the study area. We assume that each farmer faces a set of discrete, mutually exclusive choices of cereal crops (that means that a person chooses exactly one of the options, not more and not less) and these measures are assumed to depend on factors of x. Therefore, x represents a number of attributes, demographical, socio-economic characteristics of households and agro-ecological variables. The question is how, *ceteris paribus*, changes in the elements of ***x*** affect the response probabilities p(y=j/x), j = 1, 2…. J. Since the probabilities must sum to unity, p (y=j/x) is determined once we know the probabilities for j = 1, 2…j. Let *x* be a 1x K vector with first element unity. The MNL model has response probabilities:

$$P\ (\gamma = j/X) = \frac{\exp\ (x\beta_j)}{1 + \sum_{k-1}^{j}(x\ \beta_k)\ j=1,\dots,\ J} \tag{1}$$

Where βj is $K \times 1$ vector, j = 1, 2……., J.
Unbiased and consistent parameter estimates of the MNL model in equation-1 require the assumption of Independence of Irrelevant Alternatives (IIA) to hold (Deressa *et al*., 2008). More specifically, the IIA assumption requires that the probability of growing a certain cereal crop by a given household needs to be independent from the probability of choosing another cereal crop (that is, Pj/Pk is independent of the remaining probabilities). The parameter estimates of the MNL model provide only the direction of the effect of the independent variables on the dependent variable, but estimates do not represent either the actual magnitude of change nor probabilities (Greene, 2012). In the second case, MNL was used to regress on the sorghum variety choices, where y represents the sorghum variety chosen by any farming household in the study area. In order to understand the influence of the independent variables, marginal effects which measure the expected change in the probability of a particular choice were calculated in both cases as follows:

$$\partial p_i / \partial x_k = P_j\left(\beta_{jk} - \sum_{j=1}^{j-1} P_j \beta_{jk}\right)$$

(2)

4.3 Results and discussion

4.3.1 Household and farm characteristics

Results in Table 4.2 show that the 83.3% of respondents attained primary school level of education, while the remaining had either secondary, adult education or non-formal education. None of the respondents had post-secondary education level. Age wise, 88% of respondents were in the range of 21 – 60 years. The lowest percentage of respondents was in the range of 15 - 20 years. The number of years of engagement in crop production was above six which was reported by 82.9% of the respondents while for the case of livestock keeping above six years was reported by 72.8%. It is further shown in Table 4.2 that the family size of respondents was 8.4 members. This family size is large and above the rural average household size of 5.0 (URT, 2013). Importance of large families in crop production activities is stressed especially when all of the household members take part in production and/or service provision to contribute to the economy of the household.

Table 4.2: Distribution of respondents by education level, age, years in crop and livestock production

Variable	N=240	%	Variable	N=240	%
Education level			**Years in crop production**		
Primary school level	200	83.3	< 3 years	15	6.2
Secondary school level	15	6.2	3– 6 years	26	10.8
Post-secondary level	0	0	Above 6 years	199	82.9
Adult education	3	1.7			
Non-formal education	22	8.8	**Years in livestock keeping**		
Respondent age (years)			< 3 years	35	16.1
15-20	7	3.1	3– 6 years	24	11.1
21-40	95	42.2	Above 6 years	158	72.8
41-60	103	45.8	**Household size** ++	8.4 (3.39)	-
Above 60	20	8.9	**Plot size (hectares)**++	5.1 (9.53)	-

Source: survey data 2013. Note: ++ denotes values are means and standard deviation in parentheses

4.3.2 Cereal production patterns and trend

Table 4.3 shows production patterns and trends in the two growing seasons in the study districts. Of the three cereal crops, the average area of maize fields is highest (3.32 – 3.71 ha) followed by sorghum fields (3.27 – 3.66 ha) and lastly pearl millet

(2.09 -2.72 ha). Table 4.4 shows long term trends of cereal production for the two regions. In comparison with the current production trends, long term trends show a gradual increase in grain yields from 0.7 to 1.1 t/ha and 0.6 to 1.0 t/ha for sorghum and pearl millets, respectively. Similar results were reported by a previous study which estimated an increase in sorghum productivity to 0.9 t/ha in 2005 (Mbwaga *et al*., 2006). Long-term trends over ten year periods (i. e. 1991-2001 and 2001-2010) in cropped area show an increase by one third by both maize and sorghum and a decrease by two thirds for millets in Dodoma region. A striking feature, however, is observed for long-term trends for all three cereals in Singida region where the cultivated area has remained steady during both periods.

Table 4.3: Current production patterns and trend in cereal production and yield in Dodoma and Singida regions

Growing season	Crop grown	Number of cultivating households	Mean area (ha)	Std.dev	Mean production (tons)	Std. dev	Mean yield (t/ha)
	All	240					
2011/12	Sorghum	180	3.27	1.83	1.99	0.79	0.61
	Maize	201	3.32	1.61	2.18	1.12	0.66
	Pearl millet	54	2.09	1.06	1.33	0.50	0.64
2012/13	Sorghum	153	3.66	2.05	1.89	0.80	0.52
	Maize	180	3.71	1.75	2.34	1.41	0.63
	Pearl millet	45	2.72	1.56	1.16	0.57	0.43

Source: survey data 2013 NB: Multiple responses

Table 4.4: Trends in cropped area and yield (1991-2010)

Region		1991-2001	2001-2010
Dodoma	Cropped area (ha)		
	• Sorghum	134 770	161 251
	• Maize	93 956	132 416
	• Millets	61 911	22 577
	Grain yield (tons/ha)		
	• Sorghum	1.0	1.1
	• Maize	0.8	0.7
	• Millets	1.0	1.0
Singida	Cropped area (ha)		
	• sorghum	72 436	78 229
	• maize	63 469	71 125
	• Millets	37 207	32 199
	Grain yield (tons/ha)		
	• Sorghum	1.0	1.1
	• Maize	0.8	0.7
	• Millets	1.0	1.0

Source: MAFC 2009

4.3.3 Determinant factors influence on trends in cereals production

4.3.3.1 Soil type diversity

Responses of smallholder farmers on preferences of soil types where they would grow a given cereal are presented in Table 4.5. Frequencies (%) of plots reported by farmers where a given cereal was cultivated in the 2011/12 season, indicated that for maize and sorghum, soil type preferences would follow the order: *Black or grey alluvial cracking soils<Red deep heavy soils <Whitish/Reddish soils<Sandy reddish fine soils<Red sandy soils<Sandy soils along the sandy rivers*. Whereas pearl millet would follow: *Sandy reddish fine soils<Red sandy soils< Red deep heavy soils < Whitish/Reddish soils <Sandy soils along the sandy rivers< Black or grey alluvial cracking soils.* On the other hand, when farmers were asked on the soil type where sorghum was actually grown in the 2011/12 season, the frequencies (%) of plots reveal a slight different trend: *Sandy reddish fine soils=Red deep heavy soils <*

Black or grey alluvial cracking soils < Whitish/Reddish soils <Red sandy soils<Sandy soils along the sandy rivers. Black or grey alluvial cracking soils are mainly located in lowland areas and positive relationship between adoption of improved maize varieties and location of fields in the low land areas was reported by Kaliba *et al*. (2000). Other studies from the area have similarly found that soil diversity is an important factor in the strive to increase production and productivity of cereals as it allows smallholder farmers to explore a wide range of soils and soils management to ensure some crop is harvested during or beyond the main growing season of a crop (Liwenga, 2003; 2008). Elsewhere, Alumira and Rusike (2005) reported farmers' preference in Zimbabwe to grow hybrid maize seeds on clay soil type over sandy loams due to the perception that clay soil has high inherent soil fertility.

4.3.3.2 Local versus improved sorghum varieties

A total of seven improved and 16 landrace sorghum varieties were reported across the surveyed households in the two regions of central Tanzania (Table 4.6). However, there were only few dominant varieties both for improved and landrace sorghum varieties. For example, *Macia*, *Pato* and *Tegemeo* were the most dominant improved sorghum varieties which were grown by 47.90%, 20.36% and 17.96% of the farmers, respectively. In general, only five of the improved sorghum varieties were grown by more than 4% of the respondents. Similarly, among the most dominant landrace sorghum varieties grown by the households only three landrace varieties (*Lugugu*, *Langalanga* and *Gangisi*) were reported to be grown by more than 15% of the respondents. In general, landrace sorghum varieties were grown by a large proportion of the households. Similar results were reported by Westengen and Brysting (2014).

Table 4.5: Farmers crop preferences on soil types

Soil description (Local name)	Predominant crops grown	Sorghum as main crop	
		count	% of plots
Sandy reddish fine soils (*Isang'ha)*	Sorghum **(42.1)**, pearl millet(41.7), maize(21.2)	108	23.4
Red deep heavy soils (*Ng'uluhwi)*	Maize **(53.8),** sorghum(47.9), pearl millet(26.2)	105	22.7
Whitish/Reddish soils (*Tifutifu)*	Maize **(50.0),** sorghum(45.8), pearl millet(25.8)	79	17.1
Red sandy soils (*Sanghamanya)*	Pearl millet **(28.8),**sorghum(25.0), maize(21.7)	49	10.6
Sandy soils along the sandy rivers *(Msawawa)*	Pearl millet **(16.7),**sorghum(11.7), maize(9.6)	26	5.6
Black or grey alluvial soils (*Mbuga)*	Maize **(69.6),** sorghum(50.8), pearl millet(14.6)	95	20.6
Total		462	100

NB: Multiple responses; bold numbers in brackets next to crop name show a highest soil type preference reported. Source: survey data 2013.

Table 4.6: Name and frequency of distribution of improved and local sorghum varieties in 2011/2012 and 2012/2013

Improved		Local	
Name of variety	% of growers	Name of variety	% of growers
Macia	47.90	Lugugu	30.88
Pato	20.36	Langalanga	24.88
Tegemeo	17.96	Gangisi	15.67
Serena	4.79	Bangala	7.37
Wahi	4.79	Mkombituna	5.53
KARI-Mtama	2.40	Sandala	4.15
Hakika	1.80	Nkolongo	2.76
		Wela	2.76

Source: survey data 2013

There are three sorghum variety choices for the sorghum producers: improved sorghum variety only (adoption), local landrace sorghum variety only (non-adoption) and both improved and local landrace sorghum varieties (partial adoption) (Table. 4.7). The largest proportion (68%) of sample households was observed to grow both improved and local landrace sorghum varieties. About 24% of the sample households were observed to grow landrace sorghum varieties only (no adoption of improved sorghum varieties). On the other hand, the percentage of sample households growing improved sorghum varieties only was about 8%. Among all districts, the highest percentage of farmers growing improved sorghum varieties only was observed for Chamwino district, Dodoma. Overall, more than 92% of the sample households were found to grow landrace sorghum varieties, either singularly (24%) or in combination with improved sorghum varieties (68%). Mafuru *et al*. (2007) observed that increased adoption of improved sorghum varieties by smallholder farmers depend not only on the production characteristics, but also the ultimate consumer preferences, thus signifying the existence of a combination of factors important in determining the constraints to adoption of improved varieties.

Table 4.7: Household sorghum variety adoption patterns by district

District	Sorghum variety choice (% of respondents)			
	Improved variety only	Local landraces only	Both improved and landrace variety	Whole sample
Bahi	6.68	13.32	80.0	25.0
Chamwino	15.00	0.00	85.0	25.0
Iramba	8.32	50.00	41.68	25.0
Singida rural	0.00	33.32	66.68	25.0
Whole sample	7.50	24.16	68.34	100.0

Source: survey data 2013

4.3.3.3 Socio-economic factors constraining sorghum production

Perceptions of farmers on the constraints of increasing sorghum production relative to other cereals reveal diverse opinions (Fig. 4.1). The highest proportion of respondents, about 60%, strongly agree that birds scaring require extra labour, and that if care is not taken, crop damage becomes heavy thus leading to high crop losses at harvest. Threshing and winnowing drudgery as well as lack of machines or equipment to thresh sorghum were perceived by an almost equal number of respondents (~40%) as important constraints to increased sorghum production. Previous studies report lack of better threshing methods on the farm as one of the hindrances for sorghum to secure markets in the breweries even though farmers were advised to use mechanical threshers, which were mostly unavailable and difficult to manage (Rohrbach and Kiriwaggulu, 2007). But alternatively, farmers could thresh their grain on tarpaulins or on cement floors.

Moreover, from the market access and prices perspective, a big proportion of respondents (>30%) indicate that lack of established markets for sorghum is an important constraint to increased sorghum production. This was followed by price fluctuations alternating between good and bad harvest years, low farm gate prices compared to maize and lastly long distances to the markets (e.g. "*minada*[1]" and "*strategic grain reserves*"). On the other hand respondents seem to have equal opinions on the perception that maize is gradually replacing traditional staples viz. sorghum and millets and those with the perception that new (improved) sorghum varieties are not palatable in comparison with local landraces/cultivars. This shows that a good number of people in the study area still consume sorghum, and the declining percentage is probably due to lack of various processed products from sorghum flour such as bread or biscuits instead they rely only on stiff porridge "*Ugali*".

[1] These are weekly market gatherings rotating in selected villages where an assortment of commodities are traded and are considered as ready markets for cereal grains

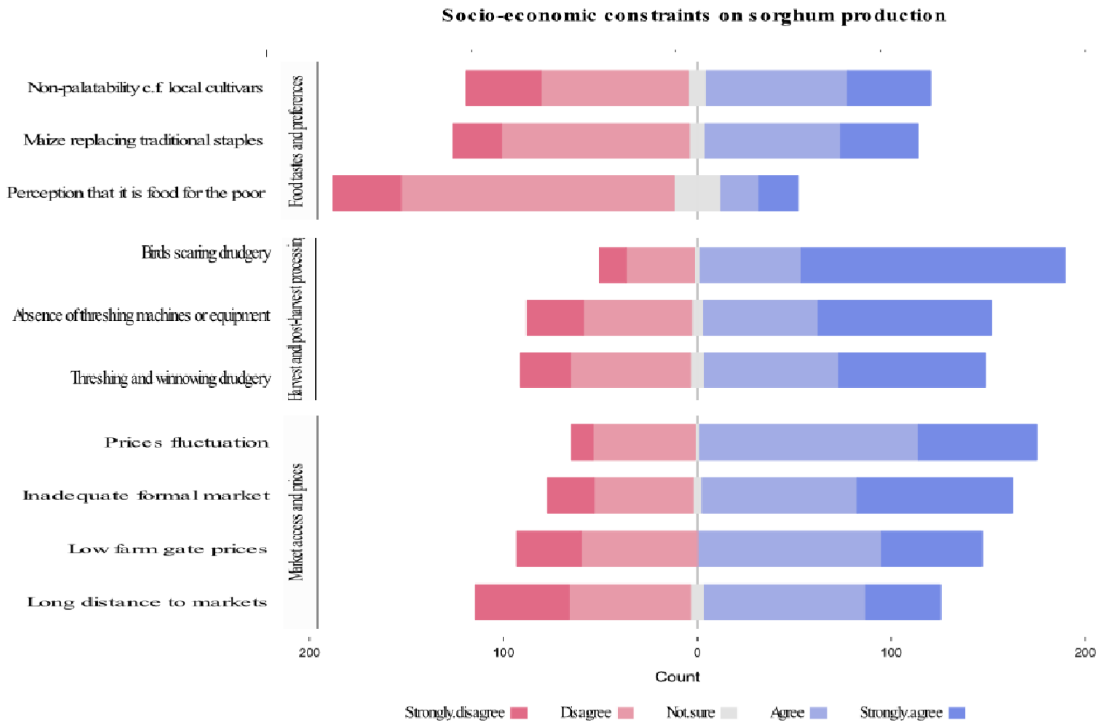


Figure 4.2: Socio-economic constraints on sorghum production

Similar findings were reported by Kebakile *et al*. (2003) in Botswana where they observed increased desire for modern products derived from sorghum flour and that the ensuing acceptability of the products depends on whether they are nutritious, healthy, and affordable and could maintain traditional flavours. However, when respondents were asked on their perception on whether sorghum is considered as food for the poor, most (80%) disagreed with the assertion.

4.3.3.4 Empirical results on factors influencing cereal crop choice

Table 4.8 presents results of the multinomial logit model which indicated that 7 out of 16 explanatory variables used in the model were statistically significant at 10% level. The chi-square value of 173.113 shows that likelihood ratio statistics are highly significant ($p<0.0001$) suggesting the model has high explanatory power. The pseudo R was 0.2885 indicating that the explanatory variable explained about

28.85% of the variation in choice of cereal crop. The results showed that age of the household head significantly influenced the likelihood of the choice of all cereals at 5% level in that for pearl millet the influence was positive, while for both sorghum and maize it was negative. They indicate that though by a small magnitude, the age of the household head increases the probability of choosing pearl millet and decreases the probability of choosing maize and sorghum. For instance a unit increase in age results in a 0.5% increase in probability of growing pearl millet, while a unit increase in age results in 0.1% and 0.4% decrease in probability of growing maize and sorghum, respectively.

Table 4.8: Marginal effects from the multinomial logit on the choice of cereal crop

Explanatory variable	pearl millet	Maize	sorghum
AGE	0.0050** (2.73)	-0.0011** (-0.39)	-0.0039** (-1.39)
EDUC	0.0054 (0.67)	0.0210 (1.54)	-0.0263 (-1.91)
PLOTSIZE	0.0025 (1.05)	-0.0088 (-2.27)	0.0063 (1.56)
HSIZE	-0.0082 (-1.34)	0.0127 (1.31)	-0.0046 (-0.45)
DISMRKT	-0.0033 (-0.56)	-0.0182 (-1.81)	0.0216 (2.05)
FEXPERIENCE	-0.1481 (-1.06)	0.2781* (1.85)	-0.1301 (-0.72)
SLTYPE1	0.1175** (2.78)	-0.2176*** (-3.06)	0.10005** (1.33)
SLTYPE2	-0.0348 (-0.91)	-0.1678 (-2.44)	0.1960 (2.86)
SLTYPE3	0.1428*** (3.04)	0.0246** (0.39)	-0.1674*** (-2.46)
SLTYPE4	0.1371*** (2.72)	-0.0044** (-0.07)	-0.1328*** (-1.88)
SLTYPE5	-0.0105 (-0.19)	-0.1493 (-1.01)	0.1465 (1.04)
SLTYPE6	-0.3616*** (-7.20)	0.2153*** (3.03)	0.1457*** (1.93)
EXTNCNT	-0.0394 (-0.98)	0.0471 (0.66)	-0.0031 (-0.05)
SUPPORT	-0.0641 (-1.46)	0.0825 (1.00)	-0.0212 (-0.24)
CLIMINFO	-0.0587* (-1.61)	-0.0354 (-0.42)	0.0869* (1.23)
TRAINING	-0.0302 (-0.61)	0.0167 (0.16)	0.0164 (0.18)

Note: ** denotes significance at 10%, ** denotes significance at 5%, *** denotes significance at 1%,* Log likelihood = -154.41945; *Prob (chi2) =0.0000;* LR chi2 (46) = 177.81; Pseudo R square = 0.2885; T-statistics in parentheses

Farming experience is an important factor influencing decision to grow maize. Results show that households with farming experience of more than six years significantly (10% level) influenced the choice of growing maize in that a unit increases in the household with > 6 years farming experience results in a 27.81% increase in probability of growing maize. Four soil types out of the six existing in the area significantly influenced the choice of cereals though with different magnitudes. For example, a unit increase in households whose fields occupy sandy reddish fine soils (*Isang'ha*) (soil type1), results in a 12% and 10% increase in probability of growing pearl millet and sorghum, respectively. Contrastingly, soil type1 results in a 22% decrease in probability of growing maize. Whitish/Reddish soils (*Tifutifu*) (soil type3) resulted in a 14% and 2% increase in probability of growing pearl millet and maize, respectively; while it resulted in a 17% decrease in probability of growing sorghum. Red sandy soils (*Sanghamanya*) (soil type4) resulted in a 14% increase in probability of growing pearl millet. On the contrary, it resulted in a 0.4% and 13% decrease in probability of growing maize and sorghum, respectively. Households owning fields with black or grey alluvial cracking soils (*Mbuga) (soil type6)* indicated a 36% decrease in probability of growing pearl millet, while they indicated a 22% and 15% increase in probability of growing maize and sorghum, respectively. Thus, for example, when we want to promote sorghum and/or maize cultivation in the expediency of soil diversity, targeting farmers with large land holdings with clay soil type may be desirable. On the other hand when promoting the cultivation of pearl millet, the promoters should target farmers whose fields are dominated with sandy and sandy loams.

The effect of access to weather forecasts/information prior to sowing was significant for pearl millet and sorghum in opposite directions. An increase in households with access to forecasted weather information resulted in decreased probability of growing pearl millet by 6% and increased the probability of growing sorghum by 9%.

4.3.3.5 Empirical results on factors influencing sorghum variety choice

Table 4.9 presents results of the multinomial logit model on sorghum variety choice. Age of household head significantly (10% level) influences the choice of sorghum varieties by farming households. It tends to decrease the probability of growing landraces and improved sorghum varieties separately but increases the probability of growing both improved and landrace sorghum varieties. For instance, a unit increase in age results in 0.4% and 0.2% decrease in probability of growing landraces and improved varieties separately, respectively, while a unit increase in age causes a 0.6% increase in probability of growing both landrace and improved sorghum varieties.

Table 4.9: Marginal effects from the multinomial logit on the choice of sorghum variety

Explanatory variable	Landraces only		Improved variety only		Both improved and landrace	
AGE	-0.0038*	(-1.59)	-0.0023	(-1.36)	0.0061*	(2.31)
EDUC	0.0200	(1.34)	-0.0053	(-0.80)	-0.0148	(-0.99)
PLOTSIZE	0.0023	(0.62)	0.0017	(0.81)	-0.0041	(-1.04)
HSIZE	-0.0099	(-1.17)	-0.0042	(-0.81)	0.0141	(1.55)
FEXPERIENCE	0.3184**	(3.30)	0.0448	(1.84)	0.3632**	(3.80)
EXTNCNT	-0.0670	(-1.16)	0.0578*	(1.61)	0.1248	(1.97)
SUPPORT	0.0264	(0.32)	-0.0544	(-1.73)	0.0279	(0.33)
CLIMINFO	-0.1435**	(-2.72)	-0.0347	(-1.06)	0.1782**	(3.05)
TRAINING	0.0216	(0.28)	0.0870	(1.16)	-0.1087	(-1.25)

Note: * *denotes significance at 10%*; ** *denotes significance at 5%*; *** *denotes significance at 1%,* Log likelihood = -147.42077; *Prob (chi2) =0.0000;* LR chi2 (32) = 83.56; T-statistics in parentheses

Farming experience significantly influences the decision to grow landraces only and both landraces and improved variety. Results show that households with farming experience of more than six years significantly (5% level) influenced the choice of growing landraces in that a unit increase in the household with > 6 years farming experience results in a 32% and 36% increase in probability of growing landraces only and both improved and landrace sorghum varieties, respectively. This could be attributed to the fact that in drought prone areas such as central semi-arid Tanzania, growing improved varieties only may prove too risky, thus variety combination may be the best option. Elsewhere, similar findings show that sorghum landraces are more likely to produce under severe drought than improved early maturing sorghum variety (Cavatassi *et al*., 2011). Moreover, planting of different crop varieties is identified as an important means of combating crop losses from pests and diseases hence increasing productivity (Di Falco *et al*., 2007).

Farmers' reception of agricultural extension services in the previous two seasons significantly (10% level) influenced the probability of growing improved varieties only. For instance a unit increase in number of households receiving extension services results in an increase of 6% probability of growing improved varieties. Similar observations were made by Abdulai and Huffman (2005) who found that the number of contacts with extension officers which is a proxy measure for access to agricultural information positively contributes to awareness and the subsequent adoption of new technologies. Access to weather forecasts/information prior to sowing was significant in that an increase in households with access to forecasted weather information resulted in decreased probability of growing landraces only by 14% and increased the probability of growing both improved varieties and landrace by 18%.

4.4 Conclusions

The Multinomial logit model results indicated that farmers' choice or not of growing a particular cereal or sorghum variety during a growing season are dependent on different socio-economic factors and agro-ecological characteristics, of which the major ones were included for this study. Farmers' ownership of land with particular soil types, age, farming experience and access to weather forecast information significantly influences the choice of a crop. On the other hand, age, farming experience, extension contact and access to weather forecast information influences sorghum variety choices. In both scenarios of choices, other factors namely household size, education of household head, agricultural support, plot size and farmers' attaining training in the past two seasons had no significant influence on the crop and/or variety choices.

Results show that harvest and post-harvest processing losses, perceptions on food tastes and preferences, and problems with market access and prices variably and strongly influence farmers' decisions to grow sorghum. Moreover, agro-ecological alongside socio-economic factors and preferences have a significant influence on choices of growing drought tolerant cereals such as sorghum and pearl millet rather than maize. Findings indicate that crop variety combination is likely the best option in cushioning the production risks. Policies in support of promoting the cultivation of improved varieties alone need to be revisited as they do not seem to guarantee increased production and productivity of the three cereals in central semi-arid Tanzania.

Based on the analyses of farmers' perceptions and empirical results, different policy options could be suggested. These include, devising simple methods to ease bird scaring drudgery, promoting fortification of sorghum and pearl millet meals to enhance palatability and tastes, facilitating the availability of ready markets and means of cushioning prices to reduce prices fluctuations. Additionally, awareness creation is required on the use of threshing machines to ease the labour burden, improved neatness of the grain for emerging markets such as breweries and increased research on the potential of growing local landraces alongside improved crop varieties rather than relying only on improved varieties.

4.5 REFERENCES

Abdulai, A. and Huffman, W. E. (2005). The diffusion of new agricultural technologies: The case of crossbred-cow technology in Tanzania. *American Journal of Agricultural Economics* 87: 645 - 659.

Ahmed, M. M., Sanders, J. H. and Nell, W. T. (2000). New sorghum and millet cultivar introduction in Sub-Saharan Africa: Impacts and research agenda. *Agricultural Systems* 64: 55 - 65.

Alumira, J. and Rusike, J. (2005). The Green Revolution in Zimbabwe. *Electronic Journal of Agricultural and Development Economics* 2 (1): 50 - 66.

Bucheyeki, T. L., Shenkalwa, E. M., Mapunda, T. X. and Matata, L. W. (2010). Yield performance and adaptation of four sorghum cultivars in Igunga and Nzega districts of Tanzania. *Communications in Biometry and Crop Science* 5 (1): 4 –10.

Below, T.B., Mutabazi, K. D., Kirschke, D., Franke, C., Sieber, S., Siebert, R. and Tscherning, K. (2011). Can farmers' adaptation to climate change be explained by socio-economic house-hold variables? *Global Environmental Change* 22: 223 – 235.

Cavatassi, R., Lipper, L. and Narloch, U. (2011). Modern variety adoption and risk management in drought prone areas; insight from the sorghum farmers of eastern Ethiopia. *Agricultural Economics* 42: 279 - 292.

Deressa, T., Hassan, R. M., Alemu, T., Yesuf, M. and Ringler, C. (2008). An analysis of determinants of farmer's choice of adaptation methods and perceptions. International Food Policy Research Institute (IFPRI), Washington, DC. 116pp.

Di Falco, J., Chavas, P. and Smale, M. (2007). Farmer management of production risk on degraded lands: the role of wheat variety diversity in the Tigray region, Ethiopia. *Agricultural Economics* 36(2): 147 – 156.

Dixon, J., Gulliver, A. and Gibbon, D. (2001). Farming systems and poverty: Improving farmers livelihoods in a changing world. FAO and World Bank, Rome and Washington, DC. 112pp.

Greene, W. H. (2012). *Econometric Analysis*. Seventh edition. Prentice Hall, New Jersey. 279pp.

Heiberger, R. M. and Robbins, N. B. (2014). Design of Diverging Stacked Bar Charts for Likert Scales and Other Applications. *Journal of Statistical Software* 57: 1 - 32

Kahimba, F. C., Mutabazi, K. D., Tumbo, S. D., Masuki, K. F. and Mbungu, F. D. (2014). Adoption and Scaling-Up of Conservation Agriculture in Tanzania: Case of Arusha and Dodoma Regions. *Natural Resources* 5: 161 - 176.

Kafle, B. (2010). Determinants of adoption of improved maize varieties in developing countries: a review. *International Research Journal of Applied and Basic Sciences* 1 (1): 1 - 7.

Kaliba, R. M. A., Verkuijl, H. and Mwangi, W. (2000). Factors affecting adoption of improved maize seeds and use of inorganic fertilizer for maize production in the intermediate and lowland zones of Tanzania. *Journal of Agricultural and Applied Economics*. 32(1): 35 - 47.

Kebakile, M. M., Mpotokwane, S. M., Motswagole, B. S., Lima de Faria, M., Santo, P., Domingues, M., and Saraiva, C. (2003). *Consumer attitudes to sorghum foods Botswana.* [*http://www.afripro.org.uk/papers/Paper12Kebakile.pd*]. Site visited on 03/06/2014.

Ley, G. J., Myaka, F. A., Heinrich, G. M. and Nyaki, A. S. (2001). Review of soil fertility and water management research, and farmers' production practices for sorghum and pearl millet-based systems in Tanzania. International Crops Research Institute for the Semi-Arid Tropics. Bulawayo, Zimbabwe. 84pp.

Liwenga, E. T. (2003). Food Insecurity and Coping Strategies in Semiarid Areas: the Case of Mvumi in Central Tanzania, Stockholm Studies in Human Geography No. 11, PhD Dissertation, Stockholm University: Department of Human Geography. 186pp.

Liwenga, E. T. (2008). Adaptive livelihood strategies for coping with water scarcity in the drylands of central Tanzania. *Physics and Chemistry of the Earth* 33: 775 - 779.

MAFC (2009). Statistics Unit-Ministry of Agriculture, Food Security and Cooperatives. National Sample Census of Agriculture 2007/2008.

Mafuru, J. M., Norman, D. W. and Langemeir, M. M. (2007). Ex-Ante adoption analysis for improved sorghum varieties in the Lake Zone Tanzania. African Crop Science Conference Proceedings 8: 1215 – 1219.

Mbwaga, A. M., Riches, C. R. and Gebissa, E. (2006). Integrated striga management to meet sorghum demand in Tanzania. [www.agry.purdue.edu/strigaconference/pdf]. Site visited on 4/6/2014.

Monyo, E. S., Ngereza, J. A., Mgonja, M. A. and Rohrbach, D. D. (2002). Adoption of improved sorghum and pearl millet technologies in Tanzania. *International Sorghum Millets Newsletter* 43: 12 - 14.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14: 53 – 67.

Rohrbach, D. D. and Kiriwaggulu, J. A. B. (2007). Commercialization prospects for sorghum and pearl millet in Tanzania. *ICRISAT Open Access Journal* 3(1):1 – 25.

SADC/ICRISAT/SMIP (Southern African Development Community/ International Crop Research Institute for the Semi- Arid Tropics/ Sorghum and Millet Improvement Programme). (1998). *Sorghum cultivars released in the SADC Region: Description and potential uses*. Bulawayo, Zimbabwe: SADC/ICRISAT SMIP (Semiformal publication.). 65pp.

URT (2001). *Agricultural Sector Development Strategy.* United Republic of Tanzania. 70pp.

URT (2013). *Key Findings Household Budget Survey 2011/12 Tanzania Mainland*. Final Report National Bureau of Statistics Tanzania. Colour printing Dar es Salaam Tanzania Limited. 196pp.

Valipour, M. (2014a). Variations of irrigated agriculture indicators in different continents from 1962 to 2011. *Advances in Water Science and Technology* 01: 01 - 14.

Valipour, M. (2014b). Future of agricultural water management in Europe based on socioeconomic indices. *Acta Advances in Agricultural Sciences* 2(7): 1 - 18.

Valipour, M. (2014c). Land use policy and agricultural water management of the previous half of century in Africa. *Applied Water Science* 3(6): 11 - 28.

Valipour, M. (2015a). Assessment of important factors for water resources management in European agriculture. *Journal of Water Resources and Hydraulic Engineering* 4(2): 169 - 178.

Valipour, M. (2015b). What is the tendency to cultivate plants for designing cropping intensity in irrigated area? *Advances in Water Science and Technology* 2(1): 1 - 12.

Valipour M. (2015c). Future of agricultural water management in Africa. *Archives of Agronomy and Soil Science* 61(7): 907 - 927.

Valipour, M., Ziatabar Ahmadi, M., Raeini-Sarjaz, M., Gholami Sefidkouhi, M. A., Shahnazari, A., Fazlola, R. and Darzi-Naftchali, A. (2015). Agricultural water management in the world during past half century. *Archives of Agronomy and Soil Science* 61(5): 657 - 678.

Waha, K., Müller, C., Bondeau, A., Dietrich, J. P., Kurukulasuriya, P., Heinke, J. and Lotze-Campen, H. (2013). Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Global Environmental Change* 23: 130 – 143.

Westengen, O. T. and Brysting, A. K. (2014). Crop adaptation to climate change in the semi-arid zone in Tanzania: the role of genetic resources and seed systems. *Agriculture and Food Security* 3(3): 1 - 12.

CHAPTER FIVE

5.0 GENERAL DISCUSSION AND CONCLUSIONS

5.1 GENERAL DISCUSSION

5.1.1 Rainfed cereal production and its vulnerability to changing climate

Although soil moisture stress is ranked as the highest constraint in crop production, more than 75% of Tanzanian smallholders depend on rainfed production systems, producing more than 98% of cereals (URT, 2013). Dryland areas are particularly vulnerable to water stress and its occurrence is a major constraint on local cereal cropping systems in Tanzania (Kangalawe and Lyimo, 2013). Rainfall throughout semi-arid areas of Tanzania is unimodal, mostly falling within the December to April period. Analyses of historical rainfall across central regions of Tanzania indicate little or no change in the amount (mean annual rainfall) but they have witnessed increase in the occurrence of extreme events in both rainfall (wet/dry years) and temperature (Kassile, 2013; Lema and Majule, 2009) which are mostly likely to be more robust than changes in mean rainfall and pose serious ramifications on crop production. Major impacts of climate change and variability on agriculture in Tanzania are a manifestation of recurrent droughts, floods, increasing crop pests and diseases and seasonal shifts (URT, 2007). Evidence established in semi-arid areas of Tabora and Dodoma is that increasing temperature and decreasing rainfall is estimated to reduce maize production by 80 and 90% and therefore threaten the main source of food for millions of Tanzanians (Mwandosya *et al*., 1998).

Sorghum being the main staple crop for the food insecure people mostly in semi-arid areas and as the second major crop (after maize) across all ecologies in Africa has received considerable attention by the researchers both from national and international collaborations (Gierend *et al*., 2014). Research efforts geared for the development of drought and heat tolerant varieties culminated into release of improved sorghum varieties with a set of recommendations in Tanzania (Monyo *et al*., 2004). The results of this study clearly show that while maize is vulnerable to climate change and its future yields are predicted to decline, overall sorghum yields are projected to be slightly higher probably due to higher tolerance to higher temperatures and drought stress. These attributes have been reported to favour the future growth performance of sorghum in semi-arid areas with lower baseline temperatures at present (Zinyengere *et al*., 2014; Gwimbi *et al*., 2013; Thornton *et al*., 2009).

Importance of adapting smallholder agriculture to variable and changing climate cannot be over emphasized. Evidence points to the fact that, in the semi-arid regions of Africa where agricultural systems rely on rainfall as a sole source of moisture for crop production, seasonal rainfall variability leads to highly variable production levels and risks (Cooper *et al*., 2008). Irrespective of whether agricultural technology is able to increase yields over the coming decades, drought and heat stress are likely to be increasingly important in determining cereal crop productivity in many regions (IPCC, 2007; Parry *et al*., 2004). Actions are required immediately that entail actions aiming at improving the resilience of the sector and reduce its vulnerability to changing climate (Bockel, 2009). Detailed studies such as the current study involving simulations of crop yields temporally and spatially are vital to inform the farming community as well as policy and decision makers. Assertions indicating the relevance and urgency of adaptation to climate variability for food security enhancement among smallholder farming communities are apparent. In that regard climate prediction and longer-term climate-change-impact assessments constitute the basis for adaptation measures, thus investigating the impacts of climate variability and change on cereal crops is warranted to assess the level of crop yield under current variability and different scenarios of climate change.

Studies on climate change impacts on agriculture in Tanzania, aggregated over the entire country or region give generalised and broad conclusions about the impact of climate change on crop production, which may not be reflective of impacts at farm or community level (e.g. Mwandosya *et al*., 1998; Moore *et al*., 2012; Kilembe *et al*., 2013). While these studies might be useful for national and regional planning, they run the risk of missing out on local peculiarities, owing to the diverse climatic and agro-ecological conditions across the country.

5.1.2 Impacts, adaptation and uncertainties in a changing climate

Results from previous studies linking climate, statistical or crop models and socio-economic analyses show that though surrounded with uncertainties, yields of maize are expected to decline with impacts of projected climate change, but biophysical impacts on sorghum and millets are yet to be studied adequately. Despite the uncertainties, however, the results from those studies have been useful in guiding public authorities and development agencies interested in food security issues on selecting and applying appropriate adaptation options. This study combined GCMs, local-scale climate variability, emissions scenarios, and crop simulation models to explore the possible range of climate change impacts on rainfed sorghum yield in central Tanzania.

While the farming community is worried about the future ramifications of climate, studies have indicated that a better understanding of the current climate creates a strong basis for a proper prognosis of future impacts on crop yields. According to Stewart (1991), the onset is a key variable to which all other seasonal rainfall attributes are related and that the onset relations determine how the season's rainfall is expected to behave. Therefore, it was deemed necessary through this study to determine the possible ranges and trends, across central Tanzania, of rainfall onset, cessation and length of growing season, as these rainfall features provide deep insight into translation of the 'rainfall variability' into the field level management options through proactive responses similar to studies by Nyakudya and Stroosnijder (2011) and Mugalavai *et al*. (2008).

Quantifying impacts and adaptation through crop simulation modelling allows understanding of how temperature and rainfall changes over time affect crop productivity and provide the impetus to push for the adaptation strategies that will alleviate further food insecurity. Evaluation was made of various adaptation strategies relative to climate change and food security such as adjustments in sowing dates, intensification of agricultural production (through fertilizer application and increase in plant densities) and adoption of improved varieties. Results reveal a good potential in undertaking farm level adaptation strategies to minimize the negative impacts of climate variability and change. They show that in order to address the information need of policy makers it is important to move from agronomic field research alone to integrated approaches combining field and simulation experiments. Simulating the effects of climate change with and without adaptation is required to continue discussions and to inform adaptation and policy initiatives at sub-continent, region, country as well as local scales in line with several studies elsewhere (Zinyengere *et al*., 2014; Berg *et al*., 2013; Knox *et al*., 2012; Thornton *et al*., 2009; Jones and Thornton, 2003).

While some studies have shown that climate variability and change would intensify many of the challenges facing dryland agriculture in many developing countries in Africa (Brown and Hansen, 2008), others indicate the potential positive impacts such as those resulting from increased rainfall (Doherty *et al*., 2009). In both scenarios, however, the expected outcomes are least known due, not only to the underlying uncertainty in the predictions of the future climate, but also because they have a limited capacity to adapt to changing circumstances (Slingo *et al*., 2005; Thomas and Twyman, 2005). Moreover, it is now evident that irrespective of the measures and policies aimed at mitigating the impacts of climate change there is an urgent need to build adaptive capacity to reduce vulnerability to climate variability and change.

5.1.3 Driving factors for farm-level decisions regarding cereals and varieties under a changing climate

The majority of farmers in the study area perceive land ownership of a particular soil type contribute to their decisions on cereal crop or variety choices during the growing season. The probability of growing pearl millet and sorghum, respectively, increased by 12% and 10% for households whose fields occupy sandy reddish fine soils perceived the least fertile soil. These households had the probability of growing maize decreased by 22%. On the other hand, farmers who perceive to have more fertile soil on their farms (with black or grey alluvial cracking soils (*Mbuga*), had a 36% decreased probability for growing pearl millet, whereas the probability of growing maize and sorghum increased by 22% and 15%, respectively. Similar studies observed the influence of soil diversity in cereal crop and varietal choices (Liwenga, 2008, 2003; Ley *et al*., 2001; Bellon and Taylor, 1993).

Farmers who have access to extension services, weather forecasts/information prior to sowing or having more farming experience are more likely to make wise trade-offs in cereal crop and variety choices with regard to prevailing stresses mainly varying rainfall patterns. Influence of socio-economic factors on farmers' decisions on whether to adopt agriculture related technologies have similarly been described by Below *et al*. (2011), Cavatassi *et al*. (2011) and Abdulai and Huffman, (2005). The major barriers to increased adoption of improved sorghum varieties are bird damage menace, fluctuating crop prices, inadequate formal market, lack of threshing machines/equipment and threshing and winnowing drudgery.

5.2 Conclusions and Recommendations

5.2.1 Conclusions

Based on the results, the following conclusions are drawn:

1. The APSIM-Sorghum model was successfully parameterized and evaluated for semi-arid central Tanzania. The parameters (genetic coefficients) determined for the sorghum cultivars are the first for the sorghum varieties dominant in Tanzania. The evaluation of the APSIM-Sorghum model in this study affirms that the model is ready to be used as a research tool in a variable agro-environment in Tanzania and elsewhere. The model successfully captured the effects of inorganic N fertilizer applications and rainfall variability on grain and biomass yield of sorghum in the area. All three cultivars can be adequately modelled with parameters that have been developed. The results suggest that APSIM can be used to predict alternate ways of improving sorghum production in central Tanzania and possibly in the whole of Tanzania.

2. Grain yield was related to their photosynthetic activity and the soil conditions. Though plants were more responsive to N fertilizer applications, deficiency in soil P limited the efficient use of applied N by the plants. Owing to the spatial variability in soil nutrients in the area, site-specific recommendation of fertilizer application is suggested for efficient fertilizer use. Though the cultivars were different, they reacted similarly to N inorganic fertilizer application. The Macia sorghum cultivar however, was more

responsive to inorganic fertilizer by producing higher grain yield than Pato and Tegemeo.

3. The study shows that climate change has a positive impact on sorghum in the semi-arid zone of central Tanzania in that its yields are projected to increase with projected increases in temperature and decrease in rainfall. However, maize productivity is projected to be negatively affected through declining yields and shortening of growing season. The model predicts a range of 5 and 21 % increase in sorghum *Macia* grain yield and between 1 and 25% decline in maize *Situka* across periods, RCPs and GCMs. This increase in sorghum yield is slight and does not guarantee food sufficiency to keep pace with the projected population, while the projected reduction in maize yields has serious implications for food security if adaptation measures are not taken.

5.2.2 Recommendations

1. The APSIM-Sorghum model was able to simulate the impact of climate change on sorghum yield and assess some adaptation measures to take. It is therefore recommended that in developing an adaptation strategy to mitigate the impact of climate change on crops, the model be used to arrive at site and season-specific adaptation measures. Combined with better prediction of the onset of the rainy season, farmers could select the right cultivar and crop in order to avoid significant yield losses and also capitalize on good seasons.

2. Although there is a large uncertainty in climate change impact on sorghum, this study emphasizes the preference of government to promote its production under variable and changing climate. Therefore, it is critical to empower smallholder farmers to adjust their farming livelihood systems as climate changes so as to respond to a range of possible future climates including unanticipated climate shocks.

3. Based on the analyses of farmers' perceptions and empirical results, different policy options could be suggested. These include, devising simple methods to ease bird scaring drudgery, promoting fortification of sorghum and pearl millet meals to enhance palatability and tastes and facilitating the availability of ready markets and means of cushioning prices to reduce prices fluctuations, availing and creating awareness in the use of threshing machines to ease the labour burden and improve quality of the grain for emerging markets such as breweries and increased research on the potential of growing local landraces alongside improved crop varieties rather than relying only on improved varieties.

4. There is need for further studies that assess the critical role cultivar maturity plays within smallholder farming systems as climate continues to change. Thus, further experimental studies are required to gather more data on the production of sorghum to fill this research gap.

5.3 REFERENCES

Abdulai, A. and Huffman, W. E. (2005). The diffusion of new agricultural technologies: The case of crossbred-cow technology in Tanzania. *American Journal of Agricultural Economics* 87: 645 - 659.

Bellon, M. R. and J. E. Taylor. (1993). Folk soil taxonomy and the partial adoption of new seed varieties. *Economic Development and Cultural Change* 41: 763 – 786.

Below, T. B., Mutabazi, K. D., Kirschke, D., Franke, C., Sieber, S., Siebert, R. and Tscherning, K. (2011). Can farmers' adaptation to climate change be explained by socio-economic variables? *Global Environmental Change* 22: 223 - 235.

Berg, A., de Noblet-Ducoudr´e, N., Sultan, B., Lengaigne, N. and Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology* 170: 89 - 102.

Bockel, L. (2009). Increasing economic resilience of agriculture sector to climate change, paper presented to the UNFCCC technical workshop on ―Increasing economic resilience to climate change and reducing reliance on vulnerable economic sectors, including through economic diversification. Cairo, Egypt, 28-30 April. [http://unfccc.int/files/adaptation/application/pdf/fao.pdf]. Site visited on 30/11/ 2011.

Brown, C. and Hansen, J. W. (2008). Agricultural Water Management and Climate Risk. Report to the Bill and Melinda Gates Foundation. IRI Tech. Rep. No. 08-01. International Research Institute for Climate and Society, Palisades, New York, USA. 19 pp.

Cavatassi, R., Lipper, L. and Narloch, U. (2011). Modern variety adoption and risk management in drought prone areas; insight from the sorghum farmers of eastern Ethiopia: *Agricultural Economics* 42: 279 - 292.

Cooper, P. J. M., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B. and Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment* 126: 24 – 35.

Doherty, R., Sitch, S., Smith, B., Lewis, S. and Thornton, P. (2009). Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology* 10: 365 -386.

Gierend, A., Ojulong, H., Letayo, E. and Mgonja, F. M. (2014). A Combined ex-post/ex-ante impact analysis for improved sorghum varieties in Tanzania. Socioeconomics Discussion Paper Series. Series Paper Number 20, 63pp.

Gwimbi, P., Thomas, T. S. and Hachigonta, S. (2013). Assessing the vulnerability of agriculture to climate change in Lesotho. In: *Southern African Agriculture and Climate Change: A Comprehensive Analysis.* (Edited by Hachigonta, S., Nelson, G. C., Thomas, T. S. and Sibanda, L. M.), International Food Policy Research Institute, Washington, DC. pp. 287 – 299.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. (Edited by Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. and Hanson, C. E.)* Cambridge University Press, Cambridge. 976pp.

Jones, P. G. and Thornton, P. K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change* 13 (1): 51 – 59.

Kangalawe, R. Y. M. and Lyimo, J. G. (2013). Climate change, adaptive strategies and rural livelihoods in semi-arid Tanzania. *Natural Resources* 4: 266 – 278.

Kassile, T. (2013). Trend analysis of monthly rainfall data in central zone. *Journal of Mathematics and Statistics* 9: 1 - 11.

Kilembe, C., Thomas, T. S., Waithaka, M., Kyotalimye, M. and Tumbo, S. (2013). *Tanzania*. In: *East African Agriculture and Climate Change: A Comprehensive Analysis. (Edited by Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M.).* IFPRI, Washington, DC. pp. 313 - 343.

Knox, J., Hess, T., Daccache, A. and Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters* 7:034032, 8pp.

Lema, M. A. and Majule, A. E. (2009). Impacts of climate change, variability and adaptation strategies on agriculture in semi-arid areas of Tanzania: The case of Manyoni District in Singida Region, Tanzania. *African Journal of Environmental Science and Technology* 3(8): 206 - 218.

Ley G. J., Myaka F. A., Heinrich G. M. and Nyaki A. S. (2001). Review of soil fertility and water management research, and farmers' production practices for sorghum and pearl millet-based systems in Tanzania. International Crops Research Institute for the Semi-Arid Tropics. Bulawayo, Zimbabwe. 84pp.

Liwenga, E. T. (2003). Food Insecurity and Coping Strategies in Semiarid Areas: the Case of Mvumi in Central Tanzania, Stockholm Studies in Human Geography No. 11, PhD Dissertation, Stockholm University: Department of Human Geography. 186pp.

Liwenga, E. T. (2008). Adaptive livelihood strategies for coping with water scarcity in the drylands of central Tanzania. *Physics and Chemistry of the Earth* 33: 775 - 779.

Monyo, E. S.; Ngereza, J.; Mgonja, M. A.; Rohrbach, D. D.; Saadan, H. M. and Ngowi, P. (2004). Adoption of improved sorghum and pearl millet technologies in Tanzania. Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics. 28 pp.

Moore, N., Alagarswamy, G., Pijanowski, B., Thornton, P., Lofgren, B., Olson, J., Andresen, J., Yanda, P. and Qi, J. (2012). East African food security as influenced by future climate change and land use change at local to regional scales. *Climatic Change* 110: 823 – 844.

Mugalavai, E. M., Kipkorir, E. C., Raes, D. and Rao, M. S. (2008). Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology* 148: 1123 – 1135.

Mwandosya, M. J., Nyenzi, B. S. and Luhanga, M. L. (1998). The Assessment of Vulnerability and Adaptation to Climate Change Impacts in Tanzania. Dar-es-Salaam, Tanzania: Centre for Energy, Environment Science and Technology (CEEST). 159pp.

Nyakudya, W. I. and Stroosnijder, L. (2011). Water management options based on rainfall analysis for rainfed maize (*Zea mays* L) production in Rushinga district, Zimbabwe. *Agricultural Water Management* 98: 1649 - 1659.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14: 53 – 67.

Slingo, J. M., Challinor, A. J., Hiskins, B. J. and Wheeler, T. R. (2005). Introduction: food crops in a changing climate. *Philosophical Transactions of the Royal Society*, Series B 360: 1983 – 1989.

Stewart, J. I. (1991). Principles and performance of response farming. In: *Climatic Risk in Crop Production. Model and Management for the Semi-arid Tropics and Sub-tropics*. *(Edited by Ford, W., Muchow, R. C., Bellamy, Z. A.)*, CAB International, Wallingford.

Thomas, D. S. G. and Twyman, C. (2005). Equity and justice in climate change adaptation amongst natural-resource-dependent societies. *Global Environmental Change* 15: 115 – 124.

Thornton, P. K., Jones, P. G., Alagarswamy, G. and Andresen, J. (2009). Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change* 19: 54 - 65.

URT (2007) United Republic of Tanzania, "National Adaptation Programme of Action (NAPA)" Division of Environment, Vice President's Office, Dar es Salaam. 61pp.

URT. (2013). *Tanzanian Agricultural Budget Report for the year 2012/2013*. Dar-es-Salaam: Tanzania Government Printer.

Zinyengere, N., Crespo, O., Hachigonta, S. and Tadross, M. (2014). Local impacts of climate change and agronomic practices on dryland crops in Southern Africa. *Agriculture, Ecosystems and Environment* 197: 1 - 10.

APPENDICES

Appendix 1: Coupled Model Intercomparison Project phase 5 (CMIP5) general circulation models considered in this study; blue (b), green (g) and red (r)

	Modelling centre	Country	Model	Lat.	Lon.	Res.	Colour
i	Commonwealth Scientific and Industrial Research Organisation/ Bureau of Meteorology (CSIRO-BOM)	Australia	ACCESS1.0	1.87	1.25	MR	g
ii	Beijing Climate Centre, China Meteorological Administration	China	BCC-CSM1.1	2.81	2.79	LR	r
iii	College of Global Change and Earth System Science, Beijing Normal University	China	BNU-ESM	2.81	2.79	LR	r
iv	Community Climate System Model, Climate and Global Dynamics Division/ National Centre for Atmospheric Research	USA	CCSM4				
v	Community Earth System Model, Climate and Global Dynamics Division/ National Centre for Atmospheric Research	USA	CESM1-BGC				
vi	Commonwealth Scientific and Industrial Research Organisation/ Queensland Climate Change Centre of Excellence (QCCCE)	Australia	CSIRO-Mk3.6	1.87	1.87	MR	g
vii	Canadian Centre for Climate Modelling and Analysis	Canada	CanESM2	2.81	2.79	LR	r
viii	Geophysical Fluid Dynamics Laboratory	US-NJ	GFDL-ESM2G	2.5	2.0	LR	r
ix		US-NJ	GFDL-ESM2M	2.5	2.0	LR	r
x	Met Office Hadley Centre	UK-Exeter	HadGEM2-CC	1.87	1.25	MR	g
xi		UK-Exeter	HadGEM2-ES	1.75	1.25	MR	g
xii	*Institut Pierre-Simon Laplace*	France	IPSL-CM5A-LR	3.75	1.89	LR	R

xiii			IPSL-CM5A-MR	2.50	1.26	LR	R
xiv	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology	Japan	MIROC-ESM	2.81	2.79	LR	r
xv		Japan	MIROC5	1.40	1.40	HR	b
xvi	Max Planck Institute for Meteorology (MPI-M)	Germany	MPI-ESM-LR	1.87	1.87	MR	g
xvii		Germany	MPI-ESM-MR	1.87	1.87	MR	g
xviii	Meteorological Research Institute	Japan	MRI-CGCM3-	1.12	1.12	HR	b
xix	Norwegian Climate Centre	Norway	Nor-ESM1-M	2.50	1.89	LR	r
xx	Institute for Numerical Mathematics	Russia	INM-CM4	2.0	1.5	MR	g