UNIVERSITY OF NAIROBI

AN AQUACROP MODEL BASED CLIMATE-SMART AGRICULTURE APPROACH FOR SMALLHOLDER FARMERS: THE CASE OF WIYUMIRIRIE, LAIKIPIA COUNTY, KENYA

BY

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A Thesis submitted in fulfillment of the Requirements for the Degree of Doctor of Philosophy in Climate Change and Adaptation of the University of Nairobi

DECLARATION

I wrote this thesis using my own words a part from certain quotations from published sources which are indicated and acknowledged accordingly. I am conscious of the University regulations on conduct of examinations more so with regard to plagiarism.

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DEDICATION

This study is dedicated to my parents albeit posthumously who, despite their advancing in age, social and cultural prejudice defied the odds to have me as their last born child who has now completed this study as a first feat of its kind in the family. Secondly, I salute my wife and sons for their understanding as I struggled with finances and time to complete this work.

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ABSTRACT

This study sought to investigate how Climate-Smart Agriculture adaptation options developed through a transdisciplinary approach, could be applied to help the Smallholder farmers of Wiyumiririe, Laikipia County, improve their food security and build resilience to Climate Change. During the incipient stages, the study determined the community's vulnerabilities as an avenue of understanding the climate related challenges farmers had, before capturing their perceptions towards the changing Climate. This was followed by identifying and prioritizing plausible Climate Smart Agriculture (CSA) options by use of pair-wise ranking and multi-criteria analysis. The options prioritized included growing of sorghum crop on two separate parcels of land; one prepared by double digging and the other one by constructing Zai pits where varying levels of farmyard manure were applied. The field trials were done from January 2016 to February 2019. Climatic trends were determined for this period which was followed by calibrating and validating Aquacrop model for Sorghum growing in a field experiment. The model output formed a basis of understanding the impacts of Climate Change on Sorghum crop yields and developing scenarios for policy makers under different climate scenarios for Wiyumiririe up to the year 2068. Further, the farmers had moderate knowledge about change. They attributed Climate Change to increased occurrence and intensity in extreme weather events such as droughts and frost. Nevertheless the farmers had the impression that Climate Change was a local phenomenon and that it could be addressed by putting in place mechanisms to support adaptation such as rainwater harvesting technologies and use of drought resistant crop varieties. This study was an attempt to put in place one such adaptation measure, through the introduction of growing sorghum, a drought resistant crop, under varying management practices. Rainfall Anomaly Index (RAI) was used to gain insight into the inter-seasonal climate variability while Standardized Precipitation Index (SPI) was used to determine inter-annual climate variability for the area. Results showed that the decadal number of wet seasons was declining; total amount of rainfall was reducing and becoming erratic, while at the same time the frequency and duration of drought periods were increasing. Further, the two meteorological indexes, i.e. RAI and SPI, were found to be useful tools in selecting suitable crop and corresponding rainwater harvesting technologies based on rainfall patterns. Calibration for Aquacrop model showed that the model attained a remarkable goodness of fit between field data and simulated ones for canopy cover, biomass and yields. Crop yields derived from Double digging and Zai pit trials were higher by 92.24% and 91.63% respectively; above the conventional farming, i.e. non CSA approach. The model output of sorghum crop yields under Climate Change in different emission scenarios varied significantly. For instance, under RCP 8.5 the yields will be higher by as much as 5.22% in the medium term, (2038) and 18.478% in long term (2068) compared to the lowest emission scenario (RCP 2.6), mainly due associated increased carbon dioxide fertilization. However the increase in yields needs to be taken with caution. This is because the compounding effects of water stress which is likely to cause a 61% reduction in canopy expansion, 31% closure in stomata and temperature stress of 31% is not yet fully understood. Moreover, the impacts of altered weather patterns to crop physiology, soil chemical properties and; prevalence of crop pests and diseases are still obscure.

To improve the performance of the interventions investigated; this study recommends calibration of Aquacrop model should include a soil fertility file, as well as tillering and ratooning aspects of Sorghum crop. Additionally, RAI and SPI should be further investigated to assess their potential in determining onset and cessation of rains. While that is being sought, the interventions investigated should be formulated into a CSA policy for Wiyumiririe. The options provide a plausible option for communities in similar environmental conditions worldwide to become food secure and resilient to Climate Change.

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LIST OF ABBREVIATIONS

B	Biomass
CC	Canopy cover
CC_x	Maximum canopy cover
CDC	Canopy decline coefficient
CGC	Canopy growth coefficient
CN	Curve number
CR	Capillary rise
d	Willmott’s index of agreement
DAP	Days after planting
Dr	Root zone depletion
E	Nash-Sutcliffe efficiency
E	Soil evaporation
ET_0	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
GDD	Growing degree-days
GCOS	Global Climate Observing System
HI	Harvest index
HI_0	Reference harvest index
K_c	Crop transpiration coefficient
K_s	Stress factor
K_{sat}	Saturated hydraulic conductivity
PWP	Permanent wilting point
RMSE	Root mean square error
S.D	Standard deviation
SAT	Saturation
SWC	Soil water content
TAW	Total available water
Tr	Crop transpiration
Vol%	Volume percentage
Vρb	Bulk density
WARMA	Water and Natural Resources Management

WP*	Normalized crop water productivity
WP	Crop water productivity
Wr	Soil water content in root zone
Y	Yield
Z	Effective rooting depth
Zx	Maximum effective rooting depth
Θ	Volumetric water content
ΘFC	volumetric water content at field capacity
ΘPWP	volumetric water content at permanent wilting point
ΘSAT	volumetric water content at saturation

GLOSSARY OF TERMS

Aqua crop Model: This is a crop model that simulates the yield of most herbaceous crops. The model takes crop development as a function of the conditions in the soil profile as well as the atmosphere. The simulation is done in four stages: Canopy cover, crop transpiration, above ground biomass and final yield.

Biomass Water Productivity (WP_b)**.** This is the aboveground dry matter (g or kg) produced per unit land area (m^2 or ha) per unit of water transpired (mm).

Calibration This is the process of estimating model data based on what is observed in the field. Rather it is fitting the model to suite the growth pattern of the crop in local conditions.

Climate Change (UNFCCC usage) A change of climate that is attributed, directly or indirectly to human activity, alters the composition of the global atmosphere and is in the addition to the natural climate variability observed over comparable periods (IPCC, 1995).

Climate According to IPCC, (1995), Climate is defined as the statistical description of the weather in terms of the mean and variability of relevant quantities over periods of several decades (typical three decades as defined by WMO).

Climate-Smart Agriculture It is an approach to agricultural production that is anchored on three pillars: Food security, i.e. sustainably increasing agricultural production and incomes Climate-Smart Agriculture. Adaptation - Adapting and building resilience to Climate Change. Mitigation - Reducing and removal of greenhouse gases wherever possible (FAO, 2010)

Climate-Smart Agriculture : In this study, it is defined as an approach to agricultural production that focus on food security, adaptation, mitigation , building resilience to Climate Change and simulating crop yields for current and future weather conditions.

Climate System: This is the part of the earth consisting of; the atmosphere: hydrosphere; Lithosphere, cynosphere and the biosphere which under the effect of the solar radiation received by the earth determines the climate of the Earth.

Conservative Crop Parameters: These are crop specific parameters required during calibration of Aquacrop model, that do not change significantly with respect to time, geographic location and management practices. In other words they are valid for all cultivars and environments; hence they do not require to be calibrated.

Drought Escaping Crops (DEC). These are crops that establish very fast and mature early before cessation of rains. Thus, they are able to escape drought.

Farmer Field School (FFS). This is an experiential learning process that emphasizes solving an agricultural problem through experimentation. The purpose of a FFS is to build capacity of farmers so that they are able to identify problems that affect their crop and livestock production systems, test possible solutions and finally encourage participants to adopt the practices that best fit their farming practices.

Food Security: World food summit (1996**)** defined food security as existing when all people at all times have access to sufficient, safe nutritious food to maintain a healthy and active life (FAO). The four components of food security are: food availability, food accessibility, food utilization and food system stability.

Goodness of Fit (GF). This is a statistical hypothesis used to test how a randomly picked sample data fits into a population with a normal distribution. In other words, it tells if sample data represents the data you would expect to find in the actual population.

Harvest Index. It is a factor or a constant that shows the relationship between biomass produced and yield. Ordinarily, biomass produced is multiplied by harvest index to get the final yields

Non -conservative crop parameters: These are parameters that are cultivar or crop specific and are mostly affected by planting and management. They include planting density, maximum canopy cover, onset of flowering, time to senescence, physiological and conditions in the soil profile.

Pair-wise ranking. It is a ranking tool used to prioritize available options. In this study, it was used to identify and prioritize suitable CSA options for adaptation and to obtain feedback about the farmers' decision making process.

Parameterization This is the standard procedure of identifying and fitting relevant parameters required to calibrate crop models within particular environmental conditions.

Rainfall Anomaly Index (RAI). This is a meteorological indices developed by Van Rooy (1965), to measure rainfall variability over seasons.

Reference Evapotranspiration (ET_O). This is a parameter used to compare the rate of evapotranspiration of a particular crop from a reference grass crop taken to be 0.12 meters tall, has a constant surface resistance of 70 s m^{-1} and an albedo effect of 0.23

Representative Concentration Pathways (RCP). The representative concentration pathways represent the range of greenhouse gas emissions that may occur during the 21st century. . They include a stringent mitigation (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0) and one scenario for very high greenhouse gas emissions (RCP 8.5).

Special Report on Emission Scenarios (SRES). This is a report by the Intergovernmental Panel on Climate Change (IPCC) that was published in 2000. The greenhouse gas emissions scenarios described in the Report have been used to make projections of possible future climate change. The SRES scenarios are "baseline" (or "reference") scenarios, which means that they do not take into account any current or future measures to limit greenhouse gas (GHG) emissions (e.g., the Kyoto Protocol to the United Nations Framework Convention on Climate Change).

Standardized Precipitation Index (SPI). The standardized precipitation index is an indicator of how observed rainfall deviates from a predetermined rainfall probability function that simulates the raw precipitation data. It was developed by researchers at Colorado State University (McKee et.al., 1993) to quantify rainfall deficit for various time intervals, which are indicators for drought.

Vulnerability: It is the degree to which a system is sensitive to, and unable to cope with adverse effects of Climate Change. It is a function of the character, magnitude, rate of Climate Change and variations to which a system is exposed, its sensitivity and adaptive capacity (Mutai and Ochola 2013). Vulnerability is thus the relationship between the degree of stress of the population (exposure), the degree of responsiveness to stress (sensitivity) and the ability to adjust to Climate Change (adaptive capacity).

CHAPTER ONE: INTRODUCTION

1.1. Background

Majority of rural Smallholder farmers resident in Sub Sahara Africa solely depend on rain-fed agriculture. Apparently, the Climate Change has emerged as one of the threats affecting this caliber of farmers. A study carried out by Waithaka, et. al., (2013), indicated that Climate Change will impact Kenya negatively mainly because of reliance on rain fed agriculture and a high population growth rate of approximately 3.7% that has not been matched by a corresponding increase in economic growth. That has resulted in endemic poverty that affects more than 50% of the population. Majority of Global Circulation Models (GCM) point to an increased but erratic rainfall for the East African region and an approximate temperature increment of 2.5^{o} C by the year 2050 based on the IPPC A1B2 scenario (Jones, et. al., 2009). The impacts are anticipated to be in form increased degradation of Agricultural land in the Arid and semi-arid lands of Kenya and more so, in the dry lands of Laikipia County, the study site because of the fragile nature of the ecosystem exacerbated by human encroachment (Gordon,et.al., 2010).

In order to improve food production and make the community resilient to Climate Change, the capacity and skills of Smallholder farmers in such regions require to be strengthened on innovative adaptation (Gordon, et. al., 2010), defined as homegrown or assimilated practices that are capable of being applied to specific locations to aid in food production. In a broad perspective, adaptation is conceptualized as the efforts made by man to forestall anticipated future climatic trends. The way communities adapt is a product of how in the first instance they are endowed to deal with negative climatic effects (IPCC 2001; Adger, et.al, 2003; IPCC 2007). Even though Climate Change is taken to be a global concern, in reality adaptation is a requirement for developing countries since vulnerabilities are high because of reliance on climate sensitive parameters, rainfall and temperature (Adger, et. al., 2003). According to Zelda, et. al., (2017), the ability of a community to adapt is determined by how in the first place it is vulnerable to Climate Change as influenced by the amount of exposure and sensitivity. A study by Adger, (2005) showed that various adaptation strategies exist which with proper guidelines farmers can put into use. In other words the options require to be customized to fit local conditions as every situation is inherently different. The current study explored an Aquacrop driven Climate smart agriculture outfit at Wiyumiririe Laikipia County to come up with suitable CSA options that could help the community enhance their food production and build resilience to climate change.

Additionally, Chambwera and Stage, (2010) correctly pointed out that unless adaptation measures are taken seriously, untrammeled changes to the climate system may have repercussions in form of impaired economic growth and other dimensions of life. Moreover, the expected climactic changes will greatly affect agricultural production which as Bryan, et. al., (2009) emphasized, provides the primary source of livelihood for the smallholder farmers' resident in rural Sub Sahara Africa.

According to (FAO, 2010), Climate-Smart Agriculture is an approach aimed at helping the managers of agricultural production systems address the issue of climate change. It is anchored on three pillars: Food security: i.e. consistently, improving production and incomes in agricultural systems; Adaptation - Making adjustments to cope and be more resilient to Climate Change; Mitigation - Ameliorating and removal of gases responsible for greenhouse effect wherever possible. This does not imply that every practice applied in every location should yield the "triple wins". Not necessarily so. The cardinal objective of CSA is to; reduce trade-offs and promote synergies so that at the end we have locally-acceptable solutions. As such, Climate-Smart Agriculture approach does not generate practices that are universally applicable; rather it develops a menu of options suitable for particular contexts and locations. Nonetheless, recent study by Chandra, et. al., (2018), averred that for CSA to be applicable in diverse locations then, cross-disciplinary approaches grounded on wide-social and political contexts are required. That is crucial so as to fully understand how the social and political dimensions are likely to influence the implementation of the options at the ground level.

There exists a host of Climate-Smart Agriculture practices which if put into practice may help alleviate food insecurity and make communities resilient to the negative effects brought by the Climate Change. According to Sandile, et. al., (2017) lack of adequate amount of water was a major handicap undermining agricultural production systems of Sub-Sahara Africa. As a consequence to that per capita food availability was low, the reason for enormous food insecurity in the region (Beintema and Stads, 2006). Those findings were in harmony with the observations made by UNESCO, (2006) in which agriculture in SSA region was found faced with a myriad of challenges such as; the urgency to produce more food using less amount of water; requirements for clean technologies; lack of empowerment that denies them opportunity to be informed on when to carry out agronomic practices; their lack of understanding on basic crop production principles in light of diminishing rainfall and rising temperatures. At Wiyumiririe, farmers have been experiencing reduced crop yields mainly because of unreliable and erratic rainfall, declining soil fertility and poor methods for harvesting rainfall water. In that regard, in order to circumvent all that, mechanisms to better capture and utilize available rainfall as well as understand the conceptual and practical interactions between the plants, soil and climate were necessary. Field experiments can be carried to explore plausible options for addressing these challenges. However the long duration it takes to develop such recommendations coupled by uncertainties associated with experiments makes such measures suspect. On the other hand, crop models when well calibrated can be an effective tool in formulating recommendations that touch on crops, soil and field management strategies for current and future weather conditions. Therefore, the core of this study involved running Aquacrop model to determine the effectiveness of the two micro-catchment water harvesting technologies (double digging and Zai pits) in improving crop yields for Seredo variety of sorghum cultivated under rain-fed Agriculture.

Aquacrop is a product of the Food and Agricultural Organization (FAO) developed to determine how crops growth, development and yields are influenced by availability of water. The parameters used are few, simple, generally intuitive and explicit but on the other hand very accurate which makes the model robust (Steduto, et. al., 2009). It's a water driven model that begins by calculating the amount of water transpired via the leaves. The product is transformed into biomass by use of a factor (water productivity) normalized for atmospheric evaporative potential and amount of carbon dioxide concentration (Steduto, et. al., 2009).
The model has wide applications such as: Generating biomass and crop yield for a given environment; Developing a performance indicator that shows the amount of yield that can be produced per unit of water lost through evaporation; Creating an understanding of how crop responds to environmental changes, i.e. by running it for dry weather conditions or for another field management; Analyzing yield gaps in which actual crop yields are compared with the potential yields that can be obtained in a particular environment; Calculating irrigation water requirement or designing an irrigation schedule; Calculating the effect of Climate Change on crop yields production; Preparing scenarios for policy makers and Plugging in the model to an economic model, a geographic information system (GIS), an irrigation platform or a hydrological model to calculate inflow and discharge of water from water shed.

The current study aimed at: determining the extent at which the Smallholder farmers were vulnerable to Climate Change, getting their perceptions and beliefs towards Climate Change, identifying, prioritizing and exploring CSA options, determining inter-seasonal and inter-annual weather trends, calibrating and validating Aquacrop model for Sorghum growing at Wiyumiririe, simulating sorghum crop yields for current and future weather conditions and preparing scenarios for policy makers. Ultimately by use of the Aquacrop model the study developed a Climate-Smart Agriculture model for Wiyumiririe that provided practical guidelines which could help the community overcome food insecurity and become resilient to the negative effects brought by Climate Change.

Remarkably, sound adaptation practices require an understanding of the causes of climate change, the impacts and desire to change behaviors. In the context of Climate Change adaptation involves making adjustments or taking advantage to actual or expected changes to the climate system. On the other hand, mitigation refers to measures that are taken to reduce accumulation of greenhouse gases in the atmosphere or enhance their sinks. In that respect, incentives for adaptation are vital premised on the fact that climate is changing and urgent actions are necessary. In the same vein observations made by (Fussel, et.,2017), pointed out that lackluster mitigation measures will not ameliorate the adverse effects of greenhouse gases that are already in the atmosphere in a way that can cause significant reduction in global warming. Therefore, alongside the ongoing mitigation responses, adaptation to climate change is required.

A study by Ajzen, (2011) showed that there was a correlation between knowledge and environmental issues to the behavior changes. For Climate Change, previous experience and personal perceptions may influence the uptake of particular adaptation options, and at times the perceptions may be at variance with observed climatic events (Meredith and Nathaniel, 2016). Rightly put, climatic trends maybe remembered for the wrong reasons, hence misinterpreted (Meredith and Nathaniel, 2016). In certain situations, individuals may have incentives to remember certain events in ways that fit their ontological perspective (Myers, et. al., 2013). Studies done by Stern, et. al., (2006); IPCC (2001); and Walthall, et. al., (2012) despite showing that agriculture as a sector contributes a significant amount of greenhouse gases also showed that the sector is vulnerable to climate. The accompanying effects have profound effects on food security (Amber, et. al., 2016). Therefore for the sector to remain viable in the face of climate change, then it has to respond with effective adaptation strategies. That will ultimately encompass making adjustments into the agricultural systems and as Smit and Skinner (2002); Walthall, et. al., (2012) suggested, take advantage of any opportunities. Effective adaptation as fronted by Smit and Skinner (2002) is profiled into four categories: Practices that target production at the farm; development of technologies; farm management and government initiated programs and insurance.

Ordinarily, practices at the farm level are geared towards production and entail: practicing irrigated agriculture, use of improved crop varieties, modifying inputs, conservation tillage, integrating, tree planting, diversifying in farm activities; change in planting date and engaging in income generating activities (Madison, 2006; Uddin, et. al., 2014). Part of this study emphasized on soil management practices, micro-catchment technologies for harvesting rain water and use of drought tolerant Seredo sorghum variety. The process of Adaptation entails a four-stage iterative learning cycle as described in the PROVIA guidance (UNEP, 2013). That is, determining vulnerabilities to climate change, identifying and choosing appropriate options for adaptation, putting the options into practice and carrying out monitoring and evaluation.

This paper presents an adaptation process to Smallholder farmers premised on Climate-Smart Agriculture, structured on the first three stages. In the first stage, the community gave an account of how they were vulnerable to Climate Change and plus their perceptions towards climate change (fig 1). In the second phase, suitable CSA adaptation options were identified and prioritized through a participatory Pair-wise ranking and Multi-criteria analysis the processes ensured that the selected strategies were relevant and socially acceptable to stakeholders (Paloma, (2018).In the third stage, the options were tried out in a field experiment, which included running the Aquacrop model. The model output formed a basis for determining the effects of the Climate Change on sorghum crop yields and developing plausible scenarios for policy makers. Figure 1 shows an overview of the methodological framework used for the study.

Stage one

1. Determined community vulnerabilities to Climate Change
2. Determined the perceptions farmers had towards Climate Change and variability
3. Evaluated the impacts of climate change to their food security

Stage two

1. Identified CSA adaptation options
2. Reviewed literature and held recursive meetings with stakeholders
3. Prioritized CSA adaptation options for on-farm trials.

Stage three

1. Prepared parcels of land. One by double digging, the other one by Zai pits
2. Administered treatments. I.e. various levels of manure and planting
3. Made field observations at regular intervals to determine: percent canopy cover, above ground biomass and soil water content at the root zone
4. Calibrated and Validated Sorghum growing for the study area
5. Run simulations for current and future weather conditions

Figure 1 : Methodological Scheme

According to Abrham, et. al., (2017) effective adaptation necessarily involves bringing onboard a number of players in collaborative research who might include; farmers, NGOs, policy makers and extension officers. Before any adaptation options are put on trial, it's of the essence to capture what the farmers believe about climate change and determine at the onset how these perceptions are in harmony or at variance with observed trends. That will work as Meredith and Nathaniel, 2016) observed, to influence their future concerns and behavior patterns and the kind of support they would require. While numerous studies have been conducted to assess the views of farmers to Climate Change such as in Australia, United Kingdom and Southern United states of America as documented by several scholars (Fleming and Vanclay 2010; Haden et al, 2012; Hogan et al., 2010; Higginbotham et al., 2013; Rejesus et al., 2013 and Donnelly et al., 2009), none has been carried out at Wiyumiririe Laikipia County Kenya. In Australia, farmers were skeptical to anthropogenic induced Climate

Change (Donnelly et al., 2009 and Higginbotham et al., 2013), while in Ethiopia Abrham et al., (2017) observed farmers attributed Climate Change to deforestation and soil degradation. Determining how farmers of Wiyumiririe Laikipia County perceived Climate Change and how those perceptions mirror observed climatic trends was important because studies done elsewhere especially in Australia, showed farmers' perceptions did not reflect observed changes (Meredith and Nathaniel, 2016). The choices farmers make to adapt to the Climate Change (real or imagined) are a factor of their perceptions and may additionally be influenced by the existence of infrastructure to support adaptation (Meredith and Nathaniel (2016). The target farmers in the current study were crucial in understanding Climate Change adaptation due to their vulnerability to climatic risks which had exposed them to food insecurity. Critical to the adaptation process was the need to sensitize them, so that they could be part and parcel of the solution to the problems brought by Climate Change and variability. Undoubtedly their perceptions and corresponding adaptation options may serve as a lesson for policy makers.

The report derived from IPCC (2007) defines vulnerability as the extent at which a particular system of interest is disposed to and incapable of coping with negative effects brought by Climate Change. Put differently, vulnerability refers to the relative sensitivity of a system when exposed to hazards, and how well it can cope with the situation (the adaptive capacity). Consequently, the vulnerability of an agricultural system is described as the exposure of crops to low amount of rainfall, how sensitive crops are prone to reduced rainfall and the corresponding capacity of farmers to cope/adapt with the situation; for instance, by planting crops that require less amount of rainfall or switching to another crop. Therefore in the context of climate change, vulnerability is described by exposure, sensitivity and adaptive capacity (IPCC, 2007). Figure 2 shows how vulnerability relates to exposure and sensitivity.

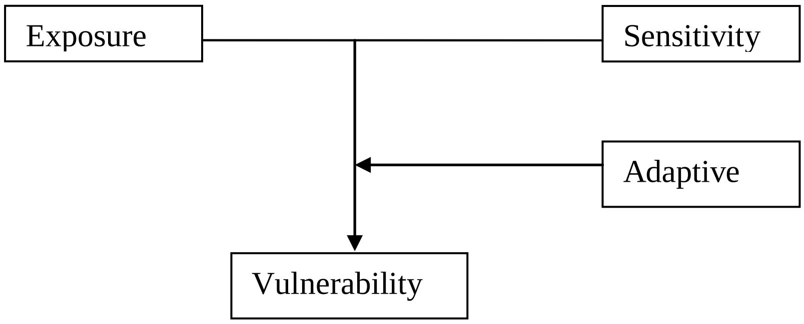


Figure 2: Relationship between vulnerability and its defining concepts

According to (Smit, et. al., 1999) a system is said to be vulnerable if it is unprotected, thus exposed, is subtle to the effects brought by Climate Change and is low in adaptive capacity

(Smit and Wandel, 2006), and vice versa. According IPCC, (2001), exposure represents the background conditions and stimuli against which a system operates and any changes in those conditions. Adger (2001) further described exposure as encompassing both the climatic variations and the degree and duration of those variations.

Sensitivity is the extent at which a system is affected either positively or negatively by a particular climate stimulus. It's a measure of how a system responds due to internal or external stimuli. Therefore, a system that's very sensitive will exemplify huge changes to minor climatic variations and vice versa. Nonetheless, a highly exposed and sensitive system doesn't necessarily mean that the system is vulnerable because on the contrary it could be having a high adaptive capacity. Adaptive capacity as defined by IPCC (2007) is the latent of a system to adjust successfully due to Climate Change: moderate potential damages: take advantage of opportunities and: cope with consequences. Additionally Adger, et.al., (2007) indicated that adaptive capacity takes into account adjustments in behavior, resources and technologies. Vulnerability is the net effect after taking into account adaptive capacity from a system that's exposed and sensitive (figure 2).

Basically two approaches are available for carrying out vulnerability assessment: the Top-down approach and the Bottom-up approach. The former mainly focuses on bio-physical of Climate Change, which by default, are readily quantifiable. Ordinarily, such an exercise may involve the application of simulation models by experts with some degree of stakeholder participation, to validate model data generated by the researchers commensurate to their objectives. The latter is a participatory process that focuses on what makes people in a particular community vulnerable to climate related hazards. Thus, the approach is location specific and relies on information collected on site. Integration of the two approaches is feasible as was in this study to bring in the transdisciplinarity aspect of the research.

Determination of climate related vulnerabilities is achieved in four steps: Defining the purpose of vulnerability assessment, planning the vulnerability assessment, assessing current vulnerability and assessing future vulnerability (Table 1)

Table 1: Procedure for Carrying out a Vulnerability Assessment

	Stages	Steps	
Involvement of relevant stakeholders	1. Defining the purpose of vulnerability assessment	1. Formulate questions that will be answered by the assessment	Iterative process
	2.Planning vulnerability assessment	Set boundaries Define the general approach to vulnerability assessment	
	3. Assessing current vulnerability	Determine the current status of the system Assess observed climate (exposure) Determine sensitivity Determine Adaptive capacity Determine overall current vulnerability	
	4. Assessing future vulnerability	Determine future exposure Determine future sensitivity Determine the future adaptive capacity Assess the overall future vulnerability	

Source. Rajagopalan 2009

1.2. Problem Statement

The Smallholder farmers of Wiyumiririe in Laikipia County are food insecure and highly vulnerable to climate related hazards owing to dearth of resources and reliance on rain fed agriculture. Laikipia County falls under the Arid and Semi-Arid Lands of Kenya and with increasing adverse effects of Climate Change, the farmers in this area are increasingly facing reduced food production. In that regard this study adopted transdisciplinary approach to investigate the contribution prioritized CSA options would have to the status of food security and adaptive capacity for the target community. Given that Climate Smart Agriculture is

both context and location specific, vulnerability assessment and evaluating farmers' knowledge about Climate Change was considered necessary.
A preliminary survey of the area showed that there were no tangible CSA measures in place that could significantly improve the farmer's adaptive capacity in a way that would make them food secure. For instance, mechanisms to harness rainwater were ineffective while soil amendments to improve soil fertility and physical properties were lukewarm. What the farmers had were shallow retention ditches and water pans which were not effective in harvesting rainwater. Besides, irrigated agriculture was absent and there was no weather forecast advisory service. Apart from maize, farmers had not diversified their crops to include drought tolerant ones. Interview with the area chief pointed out that the county government of Laikipia was active in addressing issues of food security for the residents, by encouraging them to use drought escaping crop varieties and practicing conservation agriculture. However such measures required to be captured into a workable CSA model to avoid some of the bottlenecks observed in previous interventions such as lack of appropriate methods of selecting farmers in decision making organs giving room for speculations as to the credibility of the choices they made.

Interview with the Agricultural extension officer, Ngobit ward revealed existence of credible efforts to improve crop yields by trying conservation agriculture but a coherent policy framework to capture the same was lacking. The study area receives low and unreliable rainfall. The high seasonal rainfall variability, irregularity in distribution, unpredictability in the onset and cessation of rains, frequent droughts and frost bite exacerbates the situation for a solely rain-fed Agriculture. These effects closely associated to Climate Change seemed to aggravate the situation making the farmers more food insecure and their adaptive capacity low.

This study therefore sought to investigate the contribution Climate Smart Agriculture options would make in bringing results to fruition for the farmers in a way that would improve their adaptive capacity by attaining food security. Raw field experiments to determine crop yields response to rainfall amount, temperature, soil fertility and effects of changing weather patterns are tedious, uncertain, time consuming and expensive. However crop models provide a plausible option out of the dilemma. In that respect, this study ran an Aquacrop model based field trail to aid in developing recommendations that could help the target community address food security.

1.3. Over-all Research Question

How are Smallholder farmers in Wiyumiririe Location of Laikipia County in Central Kenya adapting to the Climate Change?

1.3.1. Research Questions

1. How vulnerable are the Smallholder farmers of Wiyumiririe to Climate Change?
2. How do the farmers perceive Climate Change?
3. What coping mechanism exists to enhance food security for the residents?
4. How does the local weather affect the wellbeing and food security of the farmers?
5. How can Aquacrop model be used to help farmers make decisions in addressing food security for current and future weather conditions under Climate Change for Wiyumiririe?

1.3.2. Overall objective

To determine how suitable Climate-Smart Agricultural practices can enhance food security and strengthen the resilience to climate change for Smallholder farmers of Wiyumiririe.

1.3.3. Specific objectives

1. To carry out vulnerability assessment to Climate Change of the Smallholder farmers
2. To determine perceptions the Smallholder farmers had towards Climate Change, impacts and CSA Adaptation options for Wiyumiririe.
3. To examine the inter-seasonal and inter-annual climatic trends for Wiyumiririe.
4. To calibrate, validate and run Aquacrop model for sorghum growing at Wiyumiririe.
5. To simulate Sorghum crop yields for current and future weather conditions under Climate Change as a basis for preparing scenarios for policy makers.

1.4. Hypothesis

Climate-Smart Agriculture practices such as use of; double digging, Zai pits and Aquacrop model can be used to help the smallholders farmers enhance food security and increase their resilience to climate change

1.5. Justification and Significance of the Study

This study makes contributions to scientific and societal bodies of knowledge as well to Climate-Smart Agriculture policy and practice through a transdisciplinary inquiry into the problems brought by climate change to Smallholder farmers of Wiyumiririe Laikipia County. According to (Valerie, et. al., 2010), knowledge about climate change for future weather conditions is still unclear. Due to these uncertainties coupled by partiality and the provisionality of our knowledge about Climate Change, a paradigm shift is required to fill the epistemological gap of disciplinary, multidisciplinary and interdisciplinary discourses. Hence transdisciplinarity contextually defined as shared understanding of a problem, iteratively devising plausible solutions and integrating new knowledge back to science and societal bodies of knowledge.

It is argued in this study that through a transdisciplinary induced CSA approach, knowledge contribution by farmers and other stakeholders was key in understanding Climate Change that helped in identifying, prioritizing and trying out suitable CSA options for adaptation. By adopting transdisciplinarity the study showed the significance of bringing on-board all players during the research process in a way that ensures ownership to the problem and development of solution.

In the incipient stages the study carried vulnerability assessment which signified the importance of making Climate-Smart Agriculture adaptation options that are based on facts rather than assumptions. The use of pair-wise ranging and multi-criteria analysis implied they were effective tools for prioritizing CSA options for adaptation. The study managed to determine inter-seasonal and inter-annual weather variability for Wiyumiririe for the first time ever. The meteorological indices (RAI and SPI) used to determine the frequency and intensity of both drought and wet periods were further applied in choosing suitable crops for Climate-Smart Agriculture interventions for Wiyumiririe which makes this study outstanding. Another component of CSA adopted for the current study was the Aquacrop model. Key selling points about the model are its simplicity, robustness, accuracy, ability to use minimum data and wide applications such as those in the current study.

Even though Aquacrop has been parameterized, calibrated and validated for a number of crops and in wide geographical locations, this study was unique in that the model was run to calibrate and validate Sorghum growing for Wiyumiririe. Further, the effects of Climate Change on Sorghum yields for current and future weather conditions based on two CSA adaptation (Double digging and Zai pits) was investigated. Moreover the model was applied to develop scenarios for policy makers. Additionally, Aquacrop was used to determine the efficiency of the two CSA interventions, (double digging and Zai pits) as micro-catchment technologies for harvesting rainfall water and simulating soil water balance. These aspects of the study helped to fill knowledge gap observed in articles reviewed.

Therefore, if the CSA interventions investigated in this study are put into policy and practice the approach can be useful in solving complex climate change food insecurity related problems in similar environmental conditions worldwide.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

In this section, articles reviewed are categorized as follows: i). Global and regional climatic projections. ii). Local climatic projections and their impact to food security in Kenya. iii). Climate-Smart Agriculture practices worldwide. iv). Calibration of Aquacrop model for a variety of crops across the globe. The articles reviewed provided a background to the work already done in the field of CSA, from which knowledge and practical gaps identified were addressed in the current study.

2.2. Global and Regional Climatic Projections

The climate on earth is complex and mainly determined by solar radiation from the sun (WMO 1992). The global climate is a product of zonal climate systems, themselves derived from longitudinal, regional and local climate systems. Global climate is also influenced by other atmospheric, terrestrial and oceanic variables which are important for Climate monitoring

According to IPCC, (2014) global surface temperatures increased by approximately, 0.78^{o}c, between the years 1850 and 2012. A notable trend was observed between 1901 and 2012 when a gradual increase in temperatures was recorded leading to global warming. Moreover, besides the increment, both decadal and inter-annual variability in temperatures has been observed. The evidence of increasing temperatures has manifested inform of reduction of snow and ice on the pick of mountains and polar region and a corresponding rise on the sea level. This rise in global temperatures has been greatly associated with increasing anthropogenic derived greenhouse gases which were indeed recorded highest during the 2000 to 2010 period. Worse, this increment in greenhouse gases especially for (carbon dioxide, nitrous oxide and methane) has a compounding effect with the Earth's climate system absorbing more solar radiation leading to an exponential rise of temperatures. Tragically, according to IPCC synthesis report (2014), the concentration of these greenhouse gases is expected to rise in the 21st century causing more warming of the earth's atmosphere, perhaps causing irreversible damage to the climate system. To help understand and thus prepare possible adaptation and mitigation activities, the IPCC developed four plausible emission scenarios which the world is likely to follow during the 21st century (Fig 3).

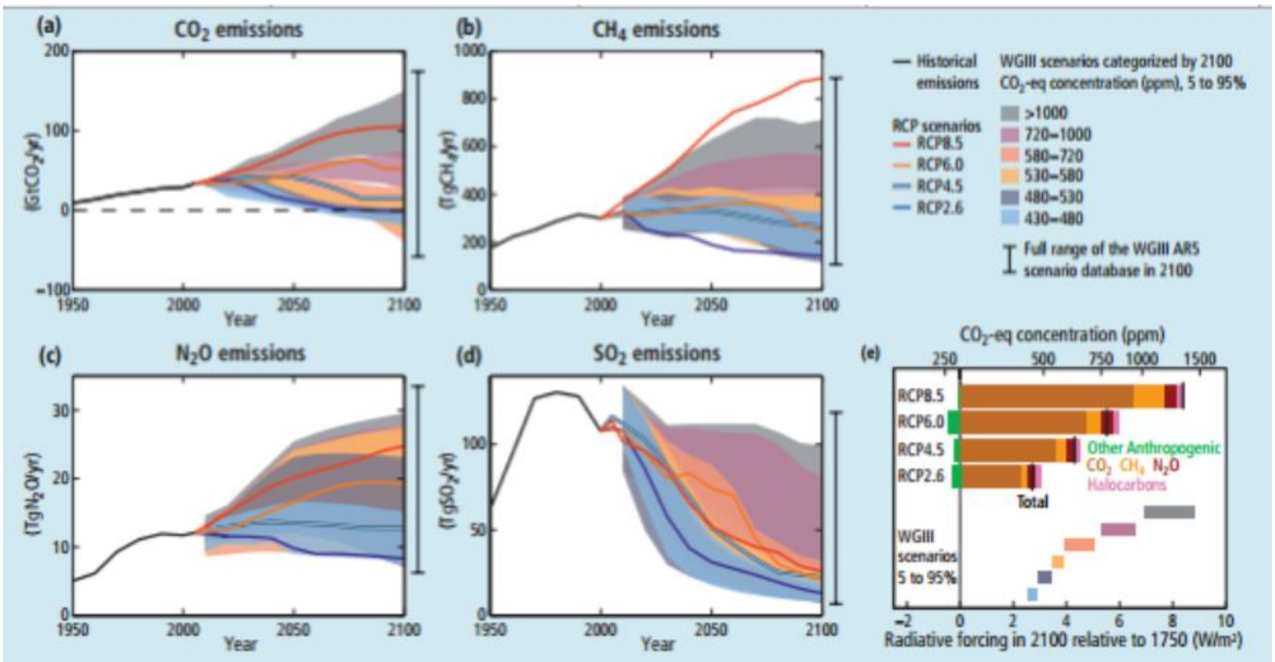


Figure 3: Representative concentration pathways (RCP).

RCP 2.6 represents a tough approach to curbing the emission of greenhouse gases; RCP 4.5 and RCP 6.0 represent moderate attempts to limit GHG emissions while; RCP 8.5, represents a situation of high emissions of GHG. (Source; IPCC, 2014)

From these findings, global surface temperatures changes towards the end of the century are likely to exceed 1.5^{o}c for the four representative concentration pathways relative to the period between 850-1900. At the same time, Warming is likely to exceed 2^{o}C for Representative concentrations 6.0 and 8.5 respectively.

Table 2: Projected changes in global terrestrial and aquatic surface temperatures and the global average rise in sea level for the mid and late 21st century compared to the 1986-2005 periods. (Source. IPCC, 2014).

		2045 to 2065		2081 to 2100	
	Scenario	Mean	Likely range	Mean	Likely range
Global mean surface temperatures (^{o}C)	RCP 2.6	1.0	0.4 to 0.6	1.0	0.3 to 1.7
	RCP 4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP 6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP 8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
Global mean sea level rise (m)	RCP 2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP 4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP 6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP 8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.32

Across Africa, temperatures have increased by 0.7^0c during the past 20th century. Additionally, general circulation models point to an increase of between 0.2^{0c} to 0.5^0c per decade in the coming years (Hulme, et al., 2001). The precipitation for future indicates that for moderate warming scenarios, sections of East Africa register increased rainfall in the range of 5%-20% between December and February and; 5%-10% between June and August, by the year 2050 (Hulme, et al., 2001). Undoubtedly these changes will have huge repercussions to water resources, human health, coastal development and agricultural production. In Kenya there is a strong agreement of climate projections among the CMIP3 ensemble models with temperatures and rainfall expected to increase by 3^0C and rainfall by 20% respectively in most parts of the country.

2.3. Local Climatic Projections and their Impacts on Food Security

According to FAO (2008), the agriculture sector contributes to food security in two perspectives; one, it's the primary source of food and secondly it's the source of livelihood for close to 36% of the World population. In East Africa it plays a bigger role because almost two thirds of the population dependent on it solely for livelihood (ILO, 2007). However despite its pivotal role, it has been found highly sensitive to climate change and as a consequence, greatly interfering with the four components of food security namely; accessibility availability, utilization and stability of the system (FAO, 2001). These effects are felt differently at global, regional and local levels. In East Africa, the effects are enormous because of reliance on rain fed Agriculture by the smallholder farmers who are the majority and practice subsistence farming (Waithaka et al., 2013).For instance, the very unpredictability nature of rains has led to a shift in the growing seasons which is of great concern because of its direct implications to food security (IPCC, 2001).

Notable changes to the climate system within East Africa were recorded between the years 1996 and 2003 in form of increased temperatures and gradual reduction in the amount of rainfall by 50 to150 mm during the months of March to May with a resounding reduction in yields for the long rainfall season crops (Funk et al., 2005). The situation suggests that Kenya as a country is likely to have serious food security issues in the next 40 years; therefore, to ameliorate and manage the negative effects brought by Climate Change; water storage was proposed as a possible avenue for addressing food security (Gosling et al., 2011). Food security is one of the big four agenda for incumbent Kenya government. For the government to realize 100% national and nutritional food security for its citizens there is need to focus on how climatic variables such as (rainfall and temperature) and micro-water technologies for harvesting rainwater can influence crop production. This study was one such effort in which the local climate for Wiyumiririe was investigated alongside Zai pits and Double digging with the objective of improving sorghum crop yields for the Smallholder farmers of Wiyumiririe.

2.4. The Concept of Representative Concentration Pathways (RCP)

These are four pathways that represent possible Climate scenarios based on the trajectories of greenhouse gases concentrations for the 21st century as adapted by IPCC 2014. These pathways succeeded the previous Special Emissions Scenarios that were in force from the year 2000. The representative concentration pathways reflect the magnitude of radiative forcing experienced to the earth's climate system for the year 2100 compared to the preindustrial estimates which were (+2.6, +4.5,+6.0 and +8.5) w/m^2 respectively (Vuuren et al., 2011). The radiative forcing can have positive or negative effects to the climate system. The positive radiative forcing trigger a rise in the earth's atmospheric temperatures while the negative forcing causes a cooling effect

The RCP 8.5: Represents a high emission scenario characterized by heavy use of fossil fuel accentuated by rapid industrialization. As a consequence of that, the amount of carbon dioxide concentration in the atmosphere will increase by three times above the current rates and methane gas will equally increase as well. The areas set aside for crop production will also increase to meet the food demands of a rising human population which by 2100 is projected to reach 12 billion. According to this pathway there will be no polices to mitigate the effects of climate change.

RCP 6.0: This is an intermediate scenario characterized by intense use of fossil fuel but significant measures to reduce emissions. The concentration of methane gas is expected to remain stable while that of carbon dioxide will increase to 70 % above the current rates before declining to 25% by the year 2100.

RCP 4.5: This is another intermediate scenario, characterized by reliance on low energy inputs coupled with intense reforestation programs, stringent measures to curb greenhouse gas emissions coupled by stabilized levels of methane gas concentrations. The carbon dioxide concentrations will however increase gradually but at around the year 2040, start declining again.

RCP 2.6: Represents a low emissions scenario characterized by a future that will depend less on fossil fuel and a world population of 9 billion by the year 2100. There will be a significant reduction in methane concentrations, but the concentrations of carbon dioxide will remain at the current rates up to the year 2020 before starting to decline and eventually turning negative by the year 2100.

The reviewed articles have demonstrated credible climate projections for the future at various levels. Few of the General Circulation Models provide accurate information besides giving that information in real time. Their ability to show climate projections to virtually every part on the surface of the world is a huge advantage. However, their lack of baseline data from actual observations contributes to variability and inconsistencies which contributes to significant inaccuracies. The development of scenarios also is a great milestone but without tying them to particular crop or livestock production systems, the information is less than convincing. To address some of these shortcomings, the current study used the observed data (obtained from a nearby Agro-metrological station operated by WALMA, for Kenya Meteorological Department) as a baseline for generating future weather conditions for Wiyumiririe and to subsequently simulate sorghum crop yields for future weather conditions under Climate Change using Aquacrop model. The model output was further used to develop scenarios for policy makers which if put into practice could help overcome food insecurity for the smallhoder farmers of Wiyumiririe.

2.5. Climate-Smart Agriculture.

2.5.1. Introduction

In this section, Climate -Smart Agriculture practices across the globe are reviewed. They range from constructing Zai pits in West Africa to using drought escaping maize varieties in South African countries.

2.5.2. Use of Zai pits

Sahel is a region of West Africa that in the past has been associated with extreme weather phenomena in the form of erratic rainfall which has greatly undermined the residents' ability to engage in meaningful agricultural production. The diversity of the region in terms of climate, soils characteristics, hydrology, topography and cultural heritage make coordination of interventions for addressing environmental challenges cumbersome. The climate is characterized by low and highly erratic rainfall. This, compounded by desertification, deforestation which has increased soil erosion, and other destructive human-related destructive activities placed the entire region under climate related threats. The effects were felt inform of drastically reduced agricultural production that caused malnutrition and starvation (Barry et al, 2008). Generally, the Sahel region is comprised of large areas with infertile soils that are prone to wind erosion. Agricultural production in the entire region characterized by: unpredictable climatic conditions characterized by frequent dry spells that result to water scarcity that is exacerbated by archaic farming practices, overstocking and overgrazing, conditions which made farming in the region precarious (Sivakummar and Wallace, 1991)

To try and overcome these challenges, construction of Zai pits was investigated alongside other four micro-water catchment techniques. For logistical purposes, Zai pits were tried out in two regions of Niger: Damari and Kakassi, while the others were explored in the neighboring countries with similar climate and soil conditions. Zai pit is a traditional water catchment technique that involves digging holes that may be 20 to 40 cms wide and 10 to 25 cms deep. Subsequently, organic manure is incorporated into the planting holes followed by the sowing of seeds. The objective of the experiments in Niger was to determine the resource-use efficiency of the Zai pits and to ameliorate crusted soils during the year 1999 and 2000 cropping season. The experiment involved the use of Zai pits and the traditional flat planting in the growth of millet. For each technique, three treatments were administered: crop residues (CR), animal manure (M) and control.

The findings of that study showed in comparison to the flat planting technique, grain yields obtained from Zai pit trials were significantly higher ($p<0.05$). The Zai pit micro-catchments enhanced the uptake of primary plant nutrients despite low manure decomposition in the pits. The pits enhanced nitrogen utilization for millet grain formation. Moreover, the pits in combination incorporated manure, lead to better utilization of water, improved soil water holding capacity that culminated to high crop yields (Barry B. et. al., 2008). From this study, it was clear that Zai pit technique was an effective method of micro-catchment of water which significantly improved crop yields of millet compared to the flat planting. Its other advantage of promoting nutrient uptake was the icing of the cake. However, this study observed that in the mentioned experiment, water balance and movement in the root zone was not monitored. Without such monitoring, it would be difficult to determine water balance in the soil profile which has a bearing to the amount of water that is lost by transpiration, which as discussed in subsequent chapters is a determinant to biomass and final yield. Therefore, the current study undertook to simulate soil water balance for Sorghum crop using the Aquacrop model to fill this knowledge gap. Through the model, it was possible to not only simulate the amount of biomass produced but as well as the grain yields for sorghum, a task not observed in the article reviewed. Simulating crop yields for current and future weather conditions under Climate Change was yet another glaring omission noted in the reviewed article which was adequately handled in this study.

2.5.3. The Climate Smart Agriculture approaches

The following section gives an account of successful global and regional Climate-Smart Agriculture initiatives (FAO, 2013).

2.5.3.1. A Climate Smart Agriculture approach for Smallholder farmers in Kenya and Tanzania

This was an initiative of the Food and Agriculture Organization (FAO). Launched in the year 2010 under the Mitigation of Climate Change Program (MICCM) targeting farmers in Kenya and Tanzania with an attempt to make agriculture more Climate-Smart. The aim was to develop a menu of practices that were site-specific through participatory assessments and consultative processes. Participating farmers in each project site were engaged first by profiling existing agricultural practices and their impact. This was followed by identifying and choosing suitable ones that could either be tried singularly or integrated into the existing ones. Further, the initiative for capacity building in CSA was linked to extension approach and incentive mechanisms (more so for dairy farmers in Kenya) and farmer field schools and a set of farmer field schools (FFS) situated in Tanzania. The outcome of the intervention was the training of 2500 participating farmers in Kenya and Tanzania on this approach. Participants constructed 300 energy saving cooking stoves, established 44 tree nurseries, transplanted of 33,500 tree seedlings and left a stock of 134,381 seedlings. Two hundred and thirty five (235) terraces were constructed to boost soil and water conservation efforts soil erosion plus the construction of two biogas digesters (FAO, 2013). These initiatives were used by FAO to evaluate the constraints that farmers faced while trying to adopt Climate-Smart agriculture options, and to identify drivers of CSA adoption practices. The findings were shared in workshops with respective national mitigation and adaptation action planners.

While these efforts were laudable and thus suited for up scaling, the whole process could be improved through a number of ways. One is by using an appropriate sampling technique in order to capture the real issues and aspirations of farmers. It was not clear from the information provided, the profile of farmers in the study. For instance, how many of the famers were women, what was their level of education and age. We just do not know, and thus it was not impossible to tell whether the proposed interventions were based on genuine needs or mare assumptions. The method of engaging participating farmers was another glaring omission. Other than documenting that they came up with a set of choices for Climate-Smart Agriculture (CSA), the article was silent on the method used to capture the views of participants. Besides that, the efficacies of the interventions were not determined empirically. For instance, how much deforestation efforts were saved from using energy saving stoves? How effective were the trees planted for mitigating against the effect of Climate Change. Thus, from a scientific perspective, the program's achievements were unverifiable.

In that regard, this study sought to address these challenges by adopting a selective sampling technique and thereafter engaging the farmers' representative through focus group discussion in identifying Climate-Smart Agriculture (CSA) practices suitable for Wiyumiririe. The farmers sampled for the current study plus their views could thus be taken as representative of the entire populace.

2.5.3.2. Sustainable Intensification of Rice Production in Vietnam

According to FAO (2013), rice production provides food to an approximate half of the world population. However paddy rice cultivation presents many challenges to the environment. First of all, irrigation consumes almost 40% of the water all over the world. The paddy fields are estimated to emit ten percent (10%) of all anthropogenic produced methane which is huge considering that the gas has 25% more greenhouse effect compared to carbon dioxide of equal amounts. In addition, the paddy field produces nitrous oxide, another greenhouse gas and also causes acid rain. To mitigate these effects, a project was launched in Dai Ghia Vietnam in the year 2006, involving alternate watering and drying (AWD), reduced seeding rates and inorganic fertilizers and greater use of organic residues. The practice entailed draining the paddy fields during grain filling that helped to reduce the amount of water required for irrigation and create a less favorable condition for methane production under anaerobic conditions. Results from the project showed significant farmers who adopted the practice registered an increment in crop yields by between 9 and 15 %; the seed rate used was lower by 70%-75%; the quantity of nitrogenous fertilizers used was less by 20-25% and; the amount of water used for irrigation was less by 33%. The huge success of the project prompted up scaling preceded by an agricultural extension partnership between Oxfam and the department responsible for plant protection (PPD) in Vietnam.

Despite the laudable success of the project, the extent of the initial farmer participation in coming up with the possible mitigation strategies remains unclear. To a large extent, the initiative was a top-down approach without grass root representation. There was no mention about vulnerability assessments carried out in the project area or farmers own inputs to the project. Such omissions are likely to undermine the sustainability of the entire exercise due to a lack of ownership by the farmers. Further, the study failed to simulate the effects of the interventions on the yields under different irrigation regimes and future climatic scenarios. With those shortcomings, it was difficult to determine whether the interventions explored were based on needs assessment or indeed whether they will be sustainable for future weather conditions. Fortunately, this study added impetus to Climate-Smart Agriculture initiatives by getting true representatives of farmers through systematic sampling, carrying out a vulnerability assessment and engaging sampled farmers in a truly recursive process in identifying suitable Climate-Smart Agriculture practices suitable for Wiyumiririe. Further, this study simulated the crop yields for current and future weather conditions, an important ingredient which ought to be integrated as a standard CSA practice if the world community will have a realistic chance of dealing with the issue of food security under Climate Change.

2.5.3.3. A Drought Tolerant Maize Variety for Improved Food Security to a section of African Farmer's

In the African context, maize is the primary source of food with more than 300 million people directly depending on it (FAO, 2013). However, according to projections, rising global temperatures and altered weather patterns, maize production my fall by 40% by the year 2030. For that reason, a need to develop and present new varieties that can adapt to the changing climate is paramount. To that end, in the year 2006, the Drought Tolerant for Africa Initiative (DTMA), developed and released 100 drought tolerant maize varieties and hybrids to over 13 African countries. Key to the success was bringing onboard all stakeholders in an inclusive process. Consequently by doing so, the project avoided the usual bottlenecks common in getting improved varieties gain access to farmers. Farmers themselves guided the breeding process thus ensuring the new varieties met local requirements. The best hybrid developed was observed to out-yield the local varieties by 26%. Certification agencies were there to fast-track the process. Seed companies reproduced the new varieties in bulk while the involvement of private sector ensured farmers had both access to inputs and market for their produce. The project was a great success as indicated by the number of farmers who adopted the new varieties including in countries that were not initially in the DTMA project. Farmers reported an increase in yields of between 20%-30% above what they ordinarily obtained from conventional varieties.

Undoubtedly, the successes of the initiative were worth commendation and should possibly be out scaled to cover the entire African continent. While that is being considered, it is essential to highlight some inherent shortcomings of the initiative which if addressed, may make future CSA initiatives more responsive. Maize for most of the African farmers is cultivated under rain fed agriculture. With the Climate Change likely to cause a rise in temperatures and alter rainfall patterns, there is need to determine how the yields will be for future weather conditions under Climate Change which apparently was not done in the study reviewed. In that regard, this study calibrated Sorghum crop for Wiyumiririe. Maize like Sorghum has already been calibrated and validated by Aquacrop, but it still requires to be tuned for local conditions.

The DTMA project should have had more comprehensive weather projections for the entire region putting into consideration IPPC emission scenarios or representative concentration pathways. Developing a drought tolerant maize variety is one thing, ensuring its validity for future weather conditions is another thing altogether. By running Aquacrop as has been done in this study, it is possible to analyze actual verses potential crop yields and prepare scenarios for policy makers.

2.6. Calibration of Aquacrop model for a Variety of Crops Across the Globe

2.6.1. Introduction

The articles reviewed under this section cover calibration of Aquacrop for selected crops cross the globe and in Kenya.

2.6.2. Calibration, validation and evaluation of Aquacrop model for selected Sorghum varieties in South Africa.

According to Sandile et al (2017), Aquacrop was tested for simulating yield responses for three Sorghum genotypes using the minimum data input requirement. The experiment was carried out in two cropping seasons at Ukilinga research farm ($30^0 24^{'}$S $29^0$24’E); 805 meters above sea level located at Pietermaritzburg, Kwa Zulu Natal province the republic of South Africa. The field trial carried during the 2013/2014 season was for model calibration while that for 2014/2015 season was for model validation. The percent canopy cover, above ground biomass and final yields were the parameters considered model evaluation. The model input data were derived from observed weather data, soil profile characteristics and non-conservative crop parameters identified for the study. These none- conservative crop parameters included: planting date, planting density, time to crop establishment, maximum canopy cover and time to reaching maximum canopy cover, time to flowering and duration of flowering and time to start canopy senescence and attain physiological maturity. The model was tested to compare observed data verses simulated ones using three built-in statistical indices; the root means square, coefficient of determination and index of agreement. Results from the study showed there was good agreement between observed and simulated values for soil water content and canopy cover for all the Sorghum genotypes. However the model was inaccurate and thus overestimated both biomass and yields perhaps as a carry over for the model insensitivity to water stress which the study observed to be less than satisfactory. The model ability to simulate canopy development and water availability was a demonstration of its robustness especially with regard to the use of a limited number of parameters. However, the model overestimation of above ground biomass yield and insensitivity to water stress for various thresholds (leaf expansion, stomata conductance and canopy senescence) is an important consideration that this current study sought to investigate.

Despite the various thresholds for water stress in the root zone being conservative crop parameters, hence requiring no calibration, double digging, construction of Zai pits together with incorporation of organic manure as field management practice were investigated as they were likely to affect soil water balance, crop development, biomass and yield production which had not hitherto been investigated. Another aspect not adequately investigated in previous studies but addressed in the current one was how Climate Change was likely to affect crop yields, details of which are provided in the next chapter.

2.6.3. Running Aquacrop model to simulate effects of various irrigation regimes on percent canopy cover, above ground biomass and grain yields for wheat in China

In an experiment, Aquacrop was calibrated and validated and subsequently used to test the performance of winter wheat under varying planting dates and irrigation regimes (Xiu-liang et al., 2014). The experiment was carried out at Xiotangshan (44.17^{o}N, 116.433^{0}S), Beijing China. Input weather data was obtained from the local Xiotangshan metrological station while soil profile characteristics were measured directly from the field. Above ground biomass was determined by routinely cutting representative plants from each plot followed by heating at 105^{0}C then oven heating at 70^{0}C constantly to get the dry matter weight. By first of all determining leaf area index though physical measurements, canopy cover was henceforth estimated as described in Hsio et al., (2009) At harvest time, dry weights were obtained by measuring. There is no significant difference in yields from the varieties, the mean grain yields were considered for the model input. The findings from the trial showed that the model data for calibration was very much consistent with the model data for validation. Additionally, good relationships were found between observed and simulated data for canopy cover, above ground biomass and grain yield during the four years of study. .

Whereas the outcome of that experiment was laudable and thus requiring up scaling, the reliance of water for irrigation is not a guarantee in future. According to IPCC, (2007) Climate Change will most likely interfere with rainfall patterns in many regions of the world hence there is an immediate need to find other ways of harvesting it for growing crops. The current study recognized the challenges of getting water for irrigation in dry areas like in the study site and thus opted for double digging and construction of Zai pits as micro-technique for harvesting rainwater that served the same purpose as irrigation.

2.6.4. Parameterization evaluation Aquacrop model in North-Eastern Thailand.

A field trail was conducted between July and October 2013 at Khao Suan Kwang research center (16^{0} 15'N, 102^{0} 510E) and 210m above the sea level situated in the Khoa Suan Kwang district of Khon Cean, Thailand. The purpose of the study was to increase an understanding of crop water productivity for the local agricultural systems. That necessitated calibration of Aquacrop for the local conditions so as enable get accurate readings. Thus field data for maize, sweet corn and soybean were collected. Results showed parameters that determine canopy development were reliable for the three crops under study. However, biomass production for maize could not be calibrated because of inadequate production for the expected cultivar. Further results indicated it was possible to practice rainfed maize farming even during the early presumed dry season and near optimal yields could be attained with only mild irrigation. However near maximum yields were attainable under rainfed conditions. Soybean was found to undergo substantial water deficit due to its shallow rooting system which made it hard for the crop to benefit from the high water content at lower levels. Consequently Aquacrop was found applicable and hence a useful tool for increasing water productivity of cultivated systems.

The effort to calibrate Aquacrop for three crops was laudable under rainfed and irrigated agriculture and undoubtedly will go a long way in formulating guidelines for better improvement of farming systems. The knowledge to improve water productivity was equally great. However the future crop yields for the reference crops were not undertaken which was necessary in order to get the projected yields for future climates scenarios. Similarly even though the study compared observed and simulated yields, there was no development of scenarios for policy makers that could show the status of food security for the community hence the need to do so in this current study.

2.6.5. Calibration of Aquacrop in Kenya.

2.6.5.1. Aquacrop model for French Beans.

A field trail was carried out at the Engineering department of Egerton University Njoro, Kenya between the months of July and December 2016. The aim of the study was to calibrate and validate Aquacrop model for French beans under varying irrigation regimes. Results indicated that the highest yields were obtained from the treatment of full irrigation (100%) while the lowest yields were from deficit irrigation (40%). Furthermore, the model was efficient in simulating aboveground biomass; pod yield and percent canopy cover for higher irrigation levels but was less efficient in simulating biomass and pod yields of treatments with an irrigation regime of less than 60% throughout the year.

2.6.5.2. Application Of Aquacrop Model for irrigated farming of Cabbages in Keiyo Highlands.

A field experiment was carried at Keiyo highlands ($0^0$22’45 N) and ($35^0 32^0$9). The purpose was to determine the potential of Aquacrop in simulating the growth of cabbages under nine different irrigation treatments. The trials were setup between the months of December 2011 and February 2012. Results showed that the model gave higher estimates for biomass but correct simulations for percent canopy cover and yields.

2.6.5.3. Calibration and validation of Aquacrop model for maize cultivation in the central highlands of Kenya.

In this study, Aquacrop was calibrated and validated for maize in two agro-ecological zones of central highlands of Kenya cultivated over three growing seasons. The purpose was to evaluate the potential of Aquacrop in helping farmers make good decisions that can lead to increased crop yield and reduced production risks through better utilization of rainfall water. The findings of the study indicated that there was high goodness of fit between observed and simulated data for canopy cover in both regions. However grain and biomass yield simulations were better for the sub-humid zone (0.96) for short rainfall growing season and 0.88 for the long rainfalls for the semi-arid site. Additionally results showed a high correlation between measured and simulated values for soil water content at three different depths (0-15, 15-25, 25-35). Thus, this study inferred that the high reliability of the model to simulate grain and yield implied that it was an effective tool in developing strategies which if put into practice can aid in making field management decisions for smallholder farmers in the region and perhaps elsewhere.

These studies done in Kenya are very important as they demonstrated the applicability of Aquacrop model to the local conditions which serves as an impetus. The effort to calibrate French beans was particularly laudable as the crop hasn’t been parameterized by FAO, so the new information will undoubtedly contribute to knowledge base. However as noted by Ng’etich et al., (2012), smallholder farmers in the central highlands of Kenya have been experiencing reduced crop yields due to water scarcity brought about by low and inadequate rainfall exacerbated by poor rainwater harvesting technologies. In that respect, irrigation whether full or deficit is not at present a viable option. Nevertheless, the studies demonstrated the robustness of Aquacrop model by showing good agreements between observed and simulated values for the parameters studied. However, none of the studies carried out investigated rain-water harvesting technologies or attempted to give future crop yields under different climatic scenarios. Therefore, the highlighted knowledge gaps were addressed in the current study.

CHAPTER THREE: DATA AND METHODOLOGY

3.1. Introduction

In this section methods used to achieve the study objectives are described. First is the procedure of carrying out vulnerability assessment, followed by determining the perceptions farmers had towards climate change. That is followed by procedure for determining rainfall variability, then finally the steps involved while calibrating and validating Aquacrop model. Therefore the chapter is divided into the following parts; i. Description of the study site and planting material. ii. Transdisciplinarity of the study. ii. Theoretical/principles underlying Aquacrop model. iv. Conceptual framework. v). Methods used to: a). Carrying out vulnerability assessments to Climate Change. b). Determine farmers' knowledge on Climate Change and adaptation strategies. c) Determining inter-seasonal and inter-annual weather trends for Wiyumiririe. d). Calibration and validation of Aquacrop model for cultivation of Seredo variety of Sorghum

3.2.1. The study site

The study was carried out in Shalom, Wiyumiririe location, Ngobit ward in Laikipia country

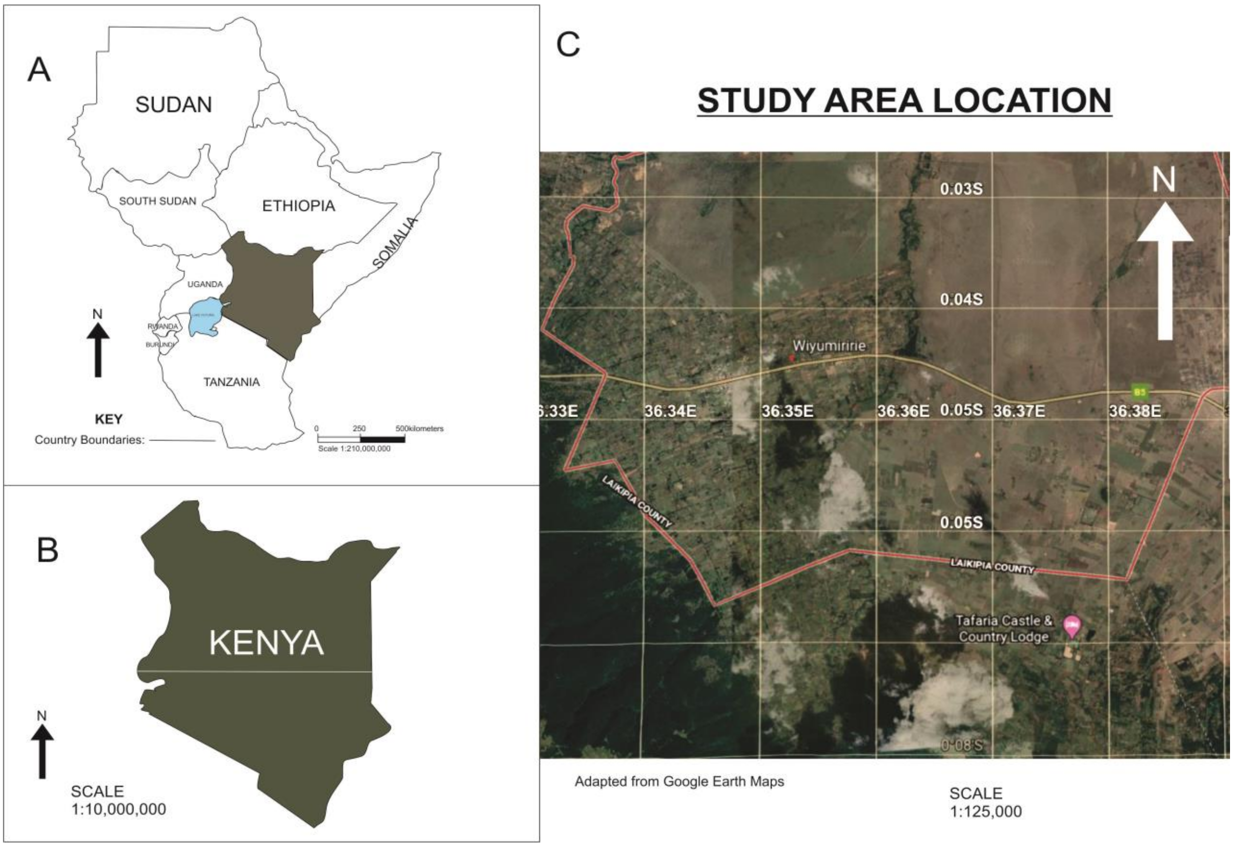


Figure 4: Wiyumiririe location in Laikipia County, Kenya.

The site was in Ngobit ward, Laikipia East constituency within the larger Laikipia County, Kenya. It is found in the southern hemisphere (S00^{0} 04.766: E036^{0}.39.174), 7212 feet above sea level and less than 20 kilometers from the equator. Ngobit ward is located about 80kms South-west of Nanyuki town and borders Nyeri and Nyandarua counties. Ngobit ward covers approximately 40 square kilometers with a population of approximately 368,686 persons in 6760 households. The main source of livelihood is mixed farming. Crop cultivated are spring onions, maize, Irish potatoes, beans and horticultural crops (Tomatoes, cabbages, French beans and bulb onions). Livestock reared are dairy cattle, sheep and indigenous poultry.

Most of the soil in Ngobit ward is black cotton soils (Montemomorilorite) and are generally fertile and suitable for crop cultivation. Phosphorus has been found to be adequate in most soils but nitrogen is inadequate. This could be attributed to the grassland nature of most of the vegetation cover which uses up a lot of nitrogen and perhaps also through nitrogen losses via volatilization. There is plenty of farmyard manure available from farmers' fields, and farmers are continuously sensitized on its potential benefits in improving soil fertility, water holding capacity, ameliorating soil acidity and moderating soil temperatures. Interview with the agricultural extension officer revealed that farmers who have adopted the practice of using it in their farms had recorded increased crop yields. Other than that, the majority of farmers use both planting and top dressing fertilizers. Nevertheless, the food security in the ward is not promising as indicated in Table 3.

Table 3: Food Security in Ngobit Ward

Ward	Population	Maize consumption per household (90kg bags)	Current stock (90 kg bags)	Duration in months for the current stock (90kg bags	Surplus (90 kg bags)	Deficit
Ngobit	36686	3057	250	<1	Nil	2803

Source: Agricultural extension officer, Ngobit ward.

Despite the presence of suitable soils for cultivation of crops, rain fed agriculture remains precarious because of inadequate and erratic rainfall exacerbated by high temperatures and sporadic strong winds. There are two rivers that flow past the Ngobit ward namely: Surguroi and Ngobit. Additionally, there are dams, water pans and boreholes, which are the primary sources of water for residents in Ngobit water. However, this water is not adequate for the increasing population. There are some limited furrow and sprinkler irrigation at Mutaro (Sirima) areas along Surguroi River.

Agricultural production in Ngobit ward is influenced by the following factors: weather patterns, capital availability, exploitation by middlemen and communication and marketing infrastructure. Changing weather patterns has had its effects in the form of prolonged drought and crop failure season after season. To address that challenge, the ministry of Agriculture has been advocating a change of farming methodology from the conventional methods to conservation agriculture. In addition, other coping mechanisms are in practice involving kitchen gardening using simple drip kits, reforestation and efficient technologies (Energy saving jikos, solar energy), promotion of drought escaping crops (DECs) such as dolicos, sweet potatoes, sorghum, pigeon peas and finger millet etc. Moreover, the county government of Laikipia has been very instrumental in assisting farmers by provision of relief seeds, assisting farmers to form marketing cooperative groups/societies and of late supporting farmers to sign contract with East Africa Malting LTD (a subsidiary of East African Breweries LTD) for sorghum growing with approximately 800 acres of land targeted to be put under the crop. The farmers will also benefit from inputs (loan –in-kind) courtesy of Laikipia County Enterprise Fund.

3.2.2. Planting Material.

Based on focus group discussion and knowledge from literature, one Sorghum genotype (Seredo) was selected for this study. Among the characteristics that favored its selection were: drought resistance, adaptability and less susceptibility to bird attack because of its relatively bitter taste. The plant grows to a height of between 150-160 cm forming outward growing tillers which ordinarily mature later than the main stem that is thicker compared to those of Serena variety. The crop flowers within 65-77 days, maturing in 110-120 days forming large heads that are oval at the base and tip. The resulting heads are brownish in color with a soft floury endosperm. In Kenya, potential production is about 4tons/ha, but the average is in the range of 1.0 to 2.8 tons/ha. In bimodal rainfall zones of Eastern province, the variety is often cultivated during the October to December short rains to allow a ratoon crop in the following (March-July) long rains. Upon maturity in February the crop is harvested and immediately ratooned to take advantage of the long rainfall season which starts mid-march. Ratooning has a benefit to the farmer in that it is possible to have more than one harvest per year. A ratoon crop has advantages in form of faster establishment, reduced labour requirements and its early maturity help crops escape attacks from the migratory Quelea birds that are usually prevalent in the months of May and June. However for the purpose of Aquacrop model calibration and to control variables, no ratoon crop was investigated in the current study. The seeds for planting were sourced from the local Agro vet shops found at Wiyumiririe.

3.2.3 Agronomic Practices.

The requirement for the Seredo variety is a fine seedbed which was attained after the initial land preparations by double digging and making of Zai pits. Planting holes were made 25mm deep at a spacing of 40cms by 30cms taking into consideration soil amendments as described in subsequent chapters. Based on the ministry of Agriculture guidelines and historical weather data, the date for planting was arrived at and coincided with when at least 20mm of rainfall had been received. Fourteen days after planting, when the crop was properly established, thinning was done to attain the correct plant population. Hand weeding was done at regular intervals to ensure no weed infestation during the entire growing period. Scouting for pests was done on weekly intervals. Harvesting was done at physiological maturity to determine biomass, yield and Harvest Index (HI).

3.3. Transdisciplinarity of the Study

Transdisciplinarity has been at the heart of scholarly discourse for over 40 years yet it has not gained a foothold into the mainstream research in academia (Vasbinder et. al., 2010). Part of the problem has been lack of a clear definition and concomitant failure to provide succinct quality standards for a truly transdisciplinary discourse. Yet according to Vasbinder et.al., (2010) science that depends purely on disciplinary discourses as opposed other mode of knowledge production will fail to correctly understand various forms of societal problems. Consequently, to address complex societal problems calls for new approaches that foster cross- disciplinary collaboration. Against this background, this section focuses on transdisciplinary research and how the process was customized for this study. Transdisciplinarity is a reflective and integrative method, propelled by scientific principles that aim to solve societal and scientific problems. The approach differentiates and integrates knowledge from both societal and scientific bodies of knowledge into one workable package (Daniel et al., 2012). According to Daniel et al. (2012), transdisciplinarity is traceable from societal problems that trigger scientific inquiry. The resulting process is collaborative and recursive relying on mutual learning process. The method is committed to new options that integrate the pathway of ‘problem solution’ and that of 'scientific innovation' that integrates interdisciplinary approaches to develop new insights (Bergmann et al., 2010). Hence, Transdisciplinarity is viewed as a sequence of three phases (fig 5)

Phase A: During this phase, the real problem affecting the smallhoder farmers of Wiyumiririe was identified. The societal problems identified were: frequent maize crop failures due to inadequate and unreliable rainfall and the lack of suitable crop germplasm to replace maize. This was compounded by lack of an effective mechanism for harvesting rainfall. The scientific gap identified was how to use available climatic, crop and soil information to help the farmers overcome the aforementioned problems. Consequently through a series of iterative sessions, the research problem was defined as high exposure and sensitivity to climatic risks which, compounded by low adaptive capacity had left the community food insecure and less resilient to Climate Change. The research questions were itemized then followed formation of the collaborative research team. Both the conceptual and methodological framework was designed. At the end of this phase, the team managed to transform the food security problem facing the farmers into a boundary subject that was researchable as provided by Clark et al., (2011).

Societal process	**Interdisciplinary process**	**Scientific process**
Societal problems	Research problem	Scientific problems

High levels of poverty
Inadequate food
Erratic and inadequate rainfall
Low crop yields
Frequent crop failures

How best can the community improve food security as gateway of building resilience to Climate Change?

How is the community vulnerable to Climate Change?
What are their perceptions about cc?
What is the weather trend?
How can Aquacrop model be used to inform decision making?

Societal discourse	Interdisciplinary discourse	Scientific discourse

Smallholder farmers
NGO-Caritas
Local administration

Vulnerability assessment
Analysis of weather data
Aquacrop model calibration and validation. Scenarios for policy makers

Agronomist
Meteorologist
Soil scientist
Key informants

Results for societal discourse	Transdisciplinary integration	Results of scientific discourse

Relevance of double digging, Zai pits for Climate change adaptation
Improved decision making

Evaluation of new knowledge contribution to societal and science discourses

Significance of vulnerability assessment; perceptions of farmers; understanding weather trend and; use of Aquacrop model for Climate Change

Figure 5: Transdisciplinary discourse of the Study.

Phase B: In this phase, there was knowledge production which involved, conducting interviews and the field trial in a process that necessitated the integration of the knowledge from farmers as well as from the research team. Thus the societal discourse which comprised of the farmers NGOs and the key informants brought onboard knowledge about the climatic risk the farmers were exposed, their sensitivity and corresponding adaptive capacity. On the other hand, the scientific discourse helped in community profiling, vulnerability assessment analysis of historical weather data, projecting future weather conditions, and running Aquacrop for future climate scenarios.

Phase C: In this phase the knowledge produced was integrated (in an ongoing process) back to the society and to the scientific bodies of knowledge as provided by Spqngenberg et.al., (2011).

3.4. Principles Underlying Aquacrop Model

3.4.1. Introduction

Field experiments can be run in order to develop recommendations for improving water efficiency. However this may take many years before valid recommendations can be formulated since it would necessitate trials to be carried out in different weather conditions, management practices and a variety of crop species. To remediate that, simulations are run with a mathematical model. When crop is cultivated in the field, production largely depends on the conditions in the soil profile, such that if water and nutrients are in abundance, the crop will grow well. However, the plant and soil interaction is linked to upper boundary by weather and water table at the lower boundary both of which are equally important for growth and development of the crop. .

The Food and Agriculture Organization (FAO) of the United Nations developed the Aquacrop model to simulate crop yields response to water stress that also includes soil fertility as a field management practice. The model was an improvement from the previous Doorenbos and Kassam (1979) method, where evapotranspiration was at the heart of calculating crop yield. The model progressed by separating crop transpiration (T_o) from soil separation (E), in the end having a program that traces canopy growth and onset of senescence as a criterion for estimating crop transpiration (Tr): Crop transpiration forms the basis of calculating biomass using normalized biomass water productivity, while the final is obtained as fraction of biomass produced using Harvest Index (HI). (Steduto et.al. 2007; Steduto et.al., 2009). The developed Aquacrop model was designed to run on daily time series. The daily time series is considered to be more appropriate as it is almost similar to the daily crop response to water stress (Acevedo et.al., 1971).

3.4.2. Description of the Aquacrop Model

The model describes how a crop growing out in the field interacts with the soil and the atmosphere (Fig 7).The model uses few parameters that are explicit and intuitive but without necessarily compromising on accuracy and that makes the model simple and robust. The parameters are either readily available or can be determined using simple methods (FAO, 2017). The environment that influences how the crop develops is determined by four inputs; Soil, Weather data, crop and management. Soil characteristics are; soil profile characteristics and groundwater characteristics respectively. It is via the roots that the plant extracts water and nutrient. Ordinarily water drains away from the system by force of gravity to the subsoil and to lower boundary. At the same time, if the ground water table is shallow, water may rise up into the root zone by capillarity. The atmosphere provides the thermal engine (rainfall, temperatures, evaporative demand and carbon dioxide concentration). That together with soil profile characteristics affects the growth and development of the crop. Hand in hand, the model considers management aspects (irrigation, mulching, weeding and soil fertility stress) as they affect crop development.

The atmospheric environment of the crop consists of five daily weather inputs: amount of rainfall, maximum and minimum air temperatures, reference evapotranspiration and annual mean carbon dioxide concentrations in the atmosphere. Rainfall and reference evapotranspiration affects water retention and movement in the root zone. Temperature influences how the crop develops while carbon dioxide concentrations affect water productivity and leaf expansion. Rainfall, temperatures are obtained from an agro-metrological station and carbon dioxide from Aquacrop database measured from Mauna Loa observatory in Hawaii. Reference evapotranspiration is determined using a built-in Penman-Monteith calculator available in Aquacrop software.

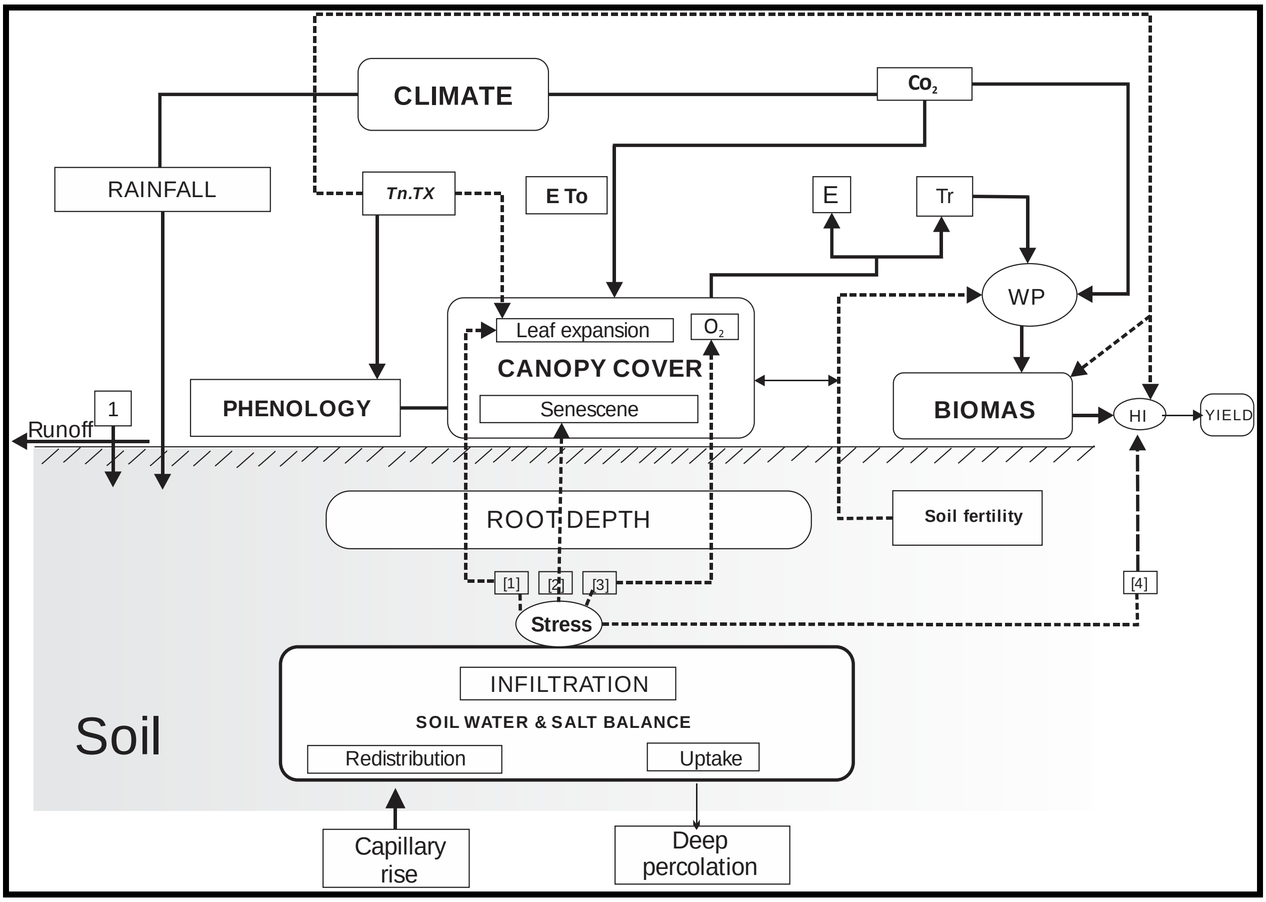


Figure 6: Description of Aquacrop model (Adapted from Aquacrop training manual)

where; (I) refers to irrigation; (1), (2), (3) and (4), refers to water stress functions for leaf expansion, canopy senescence, stomata conductance and Harvest Index (HI); Tx is the maximum air temperatures while; Tn is the minimum air temperatures; ETo is the reference evapotranspiration; E, Soil evaporation; Tr is the canopy transpiration and; qs stomata conductance. (Source: FAO 2017)

In Aquacrop soil is taken to consist of several layers of variable depth which have to be specified by the user. For each layer, the user is required to specify; soil texture, hydraulic conductivity, volumetric water content at saturation (SAT) field capacity (FC) and at permanent wilting point (PWP). From that information, Aquacrop derives other soil characteristics such as; Total amount of water available (TAW), which determines the size of water reservoir and readily evaporative water (REW), which is required in calculating the amount of water, lost via soil evaporation. That information is used to calculate capillarity rise. Hydraulic conductivity is additionally used to determine drainage coefficient (tau) and the curve number (CN), for calculating the magnitude of surface runoff. Thus on daily bases, Aquacrop performs a water balance in the root zone that takes into account; internal drainage, infiltration, deep percolation, evaporation, surface runoff, transpiration and capillarity rise (Steduto, et.al., 2009; Raes, et.al., 2009).

The crop system in Aquacrop has five components: phenology, canopy development, rooting depth, aboveground biomass production and the harvestable yield. Phenology is mainly determined by the specific cultivar and temperature changes. Aquacrop runs thermal time in growing day degrees (GDD) as the default clock. As the crop grows in the field through its phenological stages, it may experience a number of stresses. These might include: stress coefficient for canopy expansion (reduction in canopy), closure of stomata, accelerated senescence at later stages and changes in Harvest Index (HI) after the formation of reproductive stage (Steduto et. al., 2009). The amount of green cover canopy and the duration in which it is present accounts for the source of water lost through transpiration. Biomass formed is proportional to the amount of water lost via transpiration factored by use of normalized water productivity. Eventually the harvestable portion of yield is calculated by use of a Harvest Index (HI).

Therefore in Aquacrop crop yields are calculated in four major steps (Fig 7).

Step 1: Green Canopy development. To describe canopy development, Aquacrop uses the concept of green canopy cover instead of leaf area index. The green canopy cover refers to the ratio of soil surface covered by the green canopy per unit surface area. The use of green cover is preferred because: it is easy to determine and secondly, it expresses the surface of the crop that receives the energy for transpiration and subsequent biomass production. When the sun is directly above crop, a shadow is seen which represents the proportion of the earth's surface covered by the green canopy. The values are in the range of zero on bare soils to one when we have full canopy cover. It is normally expressed in percentage, from 0% to 100%. The process can be affected by water stress that subsequently affects leaf as well as canopy expansion and in severe conditions it triggers premature canopy senescence.

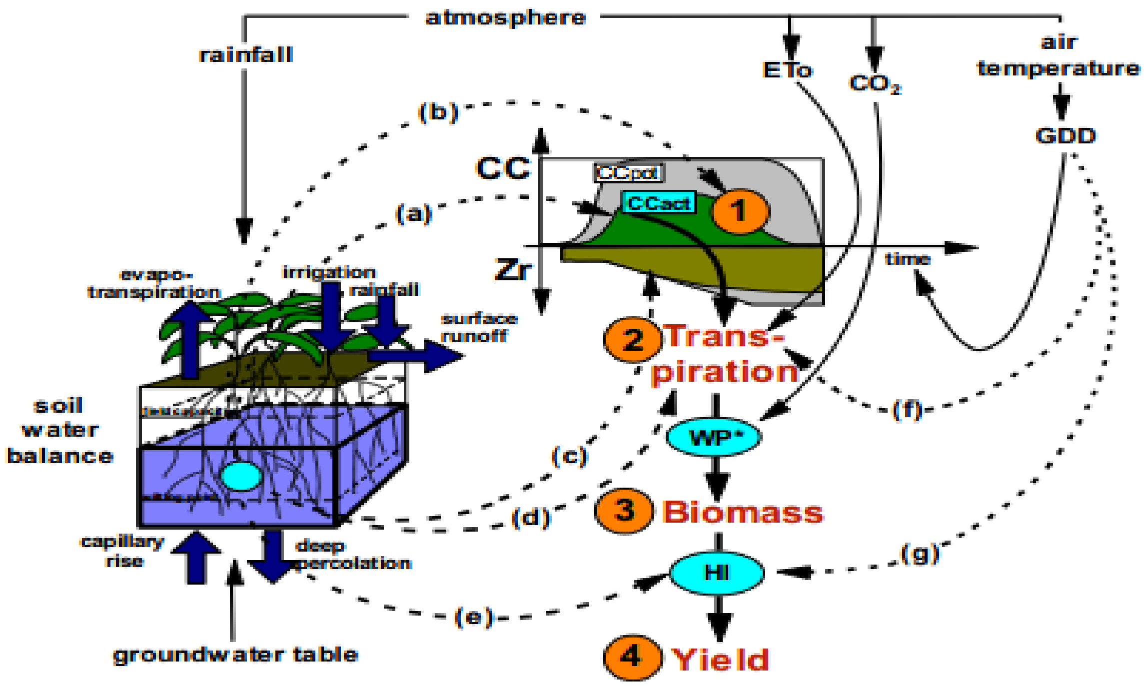


Figure 7: Calculation scheme of Aquacrop. The dotted arrows are processes affected by water stress i.e.; (from a to e) and those affected by temperature stress (from f to g). (Source: FAO, 2017)

Step 2: Crop transpiration (Tr). To simulate crop transpiration, Aquacrop uses the k_cETo method. The amount of water lost via transpiration is obtained by multiplying the computed reference evapotranspiration (ETo) with a specific crop coefficient ($K_{ctr)}$. The reference evapotranspiration is an expression of the evaporative power of the atmosphere in a particular place as dictated by weather conditions.

Thus crop transpiration TR=Kc_{tr} x Eto...1

The crop coefficient has a direct relationship with green cover canopy and keeps changing throughout the lifecycle of a crop. During this phase water and salinity stress may occur affecting crop transpiration. In such a situation a stress factor (Ks) is introduced. There is a Ks $_{(aer)}$ factor for water logging: Ks $_{(stom)}$, for stomata closure and; Ks $_{(salt}$, for soil salinity, stoma).

Step 3: Biomass. The amount of aboveground biomass produced is proportional to cumulative transpiration (∑Tr). That relationship is the cornerstone for the Aquacrop model. The reason being that the amount of water transpired is dependent on the size of canopy cover. Through the same pathway (stomata) by which plants transpires, carbon dioxide is taken and is subsequently converted to carbohydrates via photosynthesis. Carbohydrates are the building blocks for biomass. The relative factor is the normalized biomass water productivity (WP*) which makes it valid for diverse climatic conditions, seasons and carbon dioxide concentrations.

Thus, B= (∑Tr) x (WP*)………………………………………………………………2

Step 4: Crop yield. Crop yields are ultimately simulated by use of a Harvest Index (HI) which is the proportion of biomass that is harvestable. Harvest index is a conservative plant parameter but may vary from its reference value depending on timing, and degree of water and heat stresses (Steduto et al., 2009). It usually adjusted during simulation to reflect water and heat stresses. Thus crop yields;

(Y) = (B) x (HI)……………………………………………………………………..3

Crop yield for future climatic scenarios. Aquacrop also simulates crop yields for future climatic scenarios. The simulation considers; the altered weather conditions and the anticipated increase in carbon dioxide concentration. The effects of altered weather conditions on crop production are run using future climatic data. Altered weather patterns may cause water and temperature stress while in some situation will lead to increased precipitation. On the hand increases in carbon dioxide concentration, induces $C0_2$ fertilization, which causes slight reduction in crop transpiration but strongly increases biomass water productivity leading to high biomass and yields. Aquacrop simulates the combined effects of altered weather conditions and elevated carbon dioxide concentrations.

Despite the huge capabilities of the Aquacrop model, it has certain limitations; it can only simulate biomass and yields for herbaceous crops; i.e. crops that have a single growth cycle. It is point simulation model because its design is to simulate crop yields at single fields where the experimental field is taken to be homogenous. Moreover the model does not account for sideways influxes of water into or out of the soil profile (FAO, 2017).

3.5. Conceptual Framework

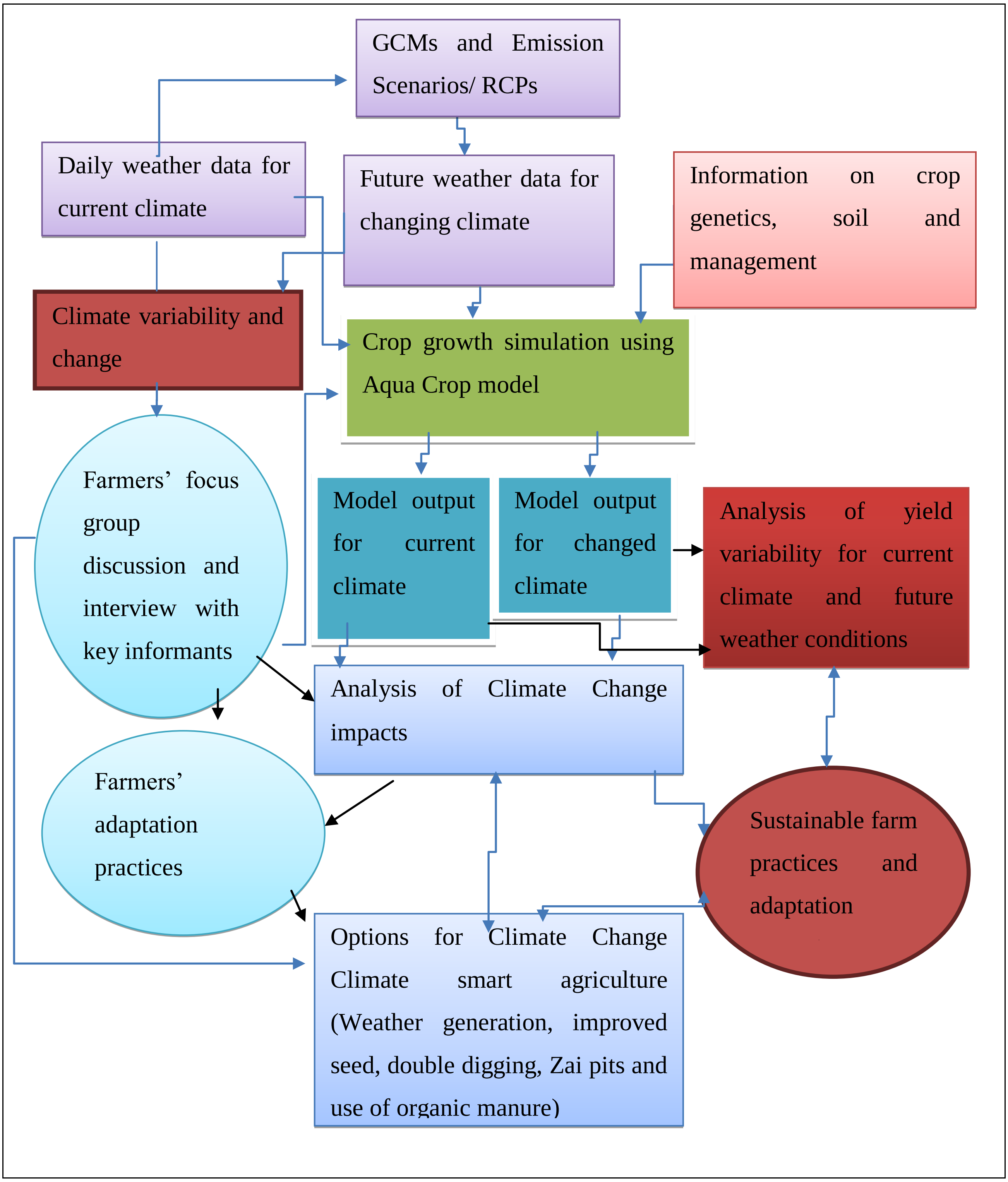


Figure 8: Conceptual Framework

3.7. Methods used to Achieve the Study Objectives

3.7.1. To carry out Vulnerability Assessment of the farmers to Climate Change

The purpose of vulnerability assessment for this study was to identify climate risks brought by Climate Change for the reference community. Thereafter, the information obtained was used in a bottom-up approach to identify and prioritize suitable CSA approaches, to help the community overcome food insecurity and adapt to Climate Change. The PRA and RRA tools used were: Resource mapping, community mapping, seasonal calendars, climatic trends, focus group discussion, key informants interviews and pair-wise ranking. The same tools had been successfully used in Uganda and Tanzania (Mwongera et al., 2017). The tools used had the advantage in that they allowed the farmers to share information and analyze their food security status in light of Climate Change. Moreover, they encouraged farmers to plan and act on knowledge created iteratively in such a way that there was ownership to the process.

A resource map is a tool that helps to define the Agro ecological zone as well as show distribution of resources within the community. To prepare a resource map, farmers were first segregated into two groups, of men and women. Then each group while guided by the main researcher gave a general locality of resources; rivers, streams, dams and boreholes. A discussion followed to build consensus and provide insights on the use of the resources over time.

Seasonal calendars were prepared mainly during focus group discussions which included a crop and a climatic calendar respectively. The purpose of the crop calendar was to identify types of crops cultivated during the whole year. That in turn helped to develop crop consumption patterns, characterize periods of food shortage and their corresponding threats affecting livelihood of the farmers. Guided by the lead researcher, farmers drew rainfall and temperature patterns for the perceived past and current climatic conditions. The calendar laid foundation for discussing the impacts of Climate Change to agricultural production.

Focus group discussions had the advantage in that they helped to; identify and rank perceived problems faced by the farmers, capture perceptions of farmers about Climate Change and impacts and, identify and prioritize Climate-Smart Agriculture practices. Further the FGDs were used to discuss livelihood options and generally how the perceived climatic changes had affected their lives. Individuals sampled by the study were interviewed to gather basic information about food security, levels of education and training, off-farm income and loans. That was followed by carrying out vulnerability assessment

To assess the current vulnerability, the study first assessed the profile of the system of interest which in this instance was: the status of natural resources available, the environmental issues that are of concern, the kind of social-economic dynamics that exist, and the developmental issues that was of immediate concern to the community. Determination of current vulnerability was achieved through the bottom-up approach by engaging farmers and other stakeholders. In the subsequent step, the study assessed the observed climate (exposure). To achieve that, once again the study employed the bottom-up approach by using climatic trend analysis, timelines and seasonal calendars.

To assess sensitivity, the study additionally used stakeholder consultations and community mapping. Key questions in assessing sensitivity were: how the observed or perceived climatic conditions had affected the system of interest, plus how the current climatic variability and extremes had impacted to the livelihood of the farmers. Response to extreme weather events (adaptive capacity), was assessed too at the community level. Key questions included: What response measures had farmers tried in dealing with climate variability and hazards? How effective had the response measures been? The tools mostly used for that were: focus group discussions, community mapping and timelines. Finally, the study appraised the overall current vulnerability by combining the outputs from the preceding steps namely: assessing the profile of the system of interest, determining exposure, sensitivity and adaptive capacity. Key questions were: What were the impacts of Climate Change to food security of the Smallholder farmers? Which groups were greatly affected? What was the level of adaptive capacity? Which were the non-climatic factors that exacerbated vulnerability and, how was the adaptive capacity distributed among the various groups within the community?

3.7.2 To determine the Farmers Perceptions about Climate Change and possible CSA Options for Adaptation.

To achieve the above objective, the study relied on qualitative and quantitative methods described by (Neuman, 2014). Semi structured interviews were conducted for individual farmers, key informants and focus group discussions. Focus group discussions were conducted separate for residents who have been there for more than 20 years, and for women and men. The researcher moderated the sessions using a checklist including vulnerabilities, perceptions and beliefs about Climate Change, climate parameters significant for the area, impacts and plausible CSA adaptation options. Key informants were knowledgeable people including: the area Agricultural extension officer, the area chief and a representative of

CARITAS, an NGO working in the area. They were purposively selected for their information on: vulnerabilities, profile of the population, government policies, soil characteristics, innovations, weather forecast, climatic impacts and community development. The local administration aided the study in profiling and sampling of the residents to cater for female headed households, educational background, economic status, gender and age groups. In village Shalom (D) each household was allocated a number ranging from 1-200. From that, each household identified with numbers 20,40,60,80,100,120,140,160,180 and 200 with the presence of one mature adult was selected. If the number corresponded to an already selected criterion, affirmative action was done within the cluster of households, e.g. between numbers 20 and 40 to get a female headed household. In the neighboring Nyambugishi village, ten farmers resident in the place for more than 30 years were purposively selected and interviewed individually for their perceived greater experience in weather trends.

To assess farmers' perceptions about Climate Change, the study created six belief typologies: 1. Perception that there's climate change and it's a global phenomenon. 2. Perception that there's climate change and it is a local phenomenon. 3. Perception that there's climate change and humans are not responsible. 4. Perception that there's climate change and humans are responsible. 5. Perception that there has not been any climate change and humans do not contribute to Climate Change. 6. Perception that there has not been any climate change but humans contribute to Climate Change. In part two of the interview, farmers recited recent and past observed extreme weather events. Fundamentally, two weather parameters, rainfall and temperatures, were found to be important. Based on that, a possibility of scenarios was presented to the respondents: 1.Has the total amount of rainfall increased/decreased/remained the same? 2. Has the long rainfall season occurred on time/delayed/came unusually too early/failed altogether? 3. Have the short rains occurred on time/delayed/came unusually too early/ failed altogether? 4. Have the temperatures increased/decreased/ or remained the same? In the third part, farmers were interviewed in focus group discussions based on the following themes: Vulnerabilities, Perceptions about Climate Change, effects of the changing climate to the agriculture sector, status of food production, coping mechanism and, CSA adaptation options. To determine their vulnerabilities, they were probed thus: what are the main challenges to food production? How does climate affect their access to water? What is their source of farm inputs? On the changing climate the groups were asked to enumerate how changes in climate had affected growing of crops, observed extreme weather events and frequency.

To identify and prioritize Climate-Smart Agriculture adaptation options, multi-criteria analysis and pair-wise ranking were used. The process began by identifying and specifying Climate-Smart Agriculture strategies considered by various stakeholders. Given the importance of agriculture and its vulnerabilities to Climate Change, the stakeholders required to evaluate and prioritize CSA practices relevant for Wiyumiririe. Following advice from experts, literature review and stakeholder consultations, a list of plausible CSA adaptation options were developed together with criteria for evaluating the options. The criteria were: i. Capacity to generate adequate crop yields ii. Legal and political implementing feasibility. iii. Capacity to withstand dry spell. iv. Financial feasibility. v. Capacity to improve soil fertility. vi. Speed of implementation. Farmers in FGDs and using maize grains did pair-wise ranking to prioritize the CSA options. Eventually, the findings from the various groups were consolidated during recursive meetings involving all stakeholders where the options for this study were adopted.

The discussions were held at the local ACK church on 20th June 2015, while key informants interviews were carried out in their respective offices on 25th and 26th June 2015. On the day of discussion, all group members walked to the site, and the participants were offered refreshments. The discussion was conducted in kikuyu language and recorded. A local community elder ushered in the facilitator and aided in clarifying questions and responses. The discussions paved way for three consecutive recursive meetings with all stakeholders between 1st July 2015 and 10th August 2015, during which transdisciplinary team was constituted, research problem identified and formulated, a design for the research process set up; community vulnerabilities outlined, impacts due to Climate Change identified, options for adaptation identified and prioritized and, transdisciplinary research timelines agreed upon.

The transdisciplinary team comprised of: Twenty seven Smallholder farmers, An Agricultural extension officer, a soil scientific, a practitioner from meteorological department, NGO representatives and the main researcher. Farmers provided their perceptions and beliefs about Climate Change, helped to capture vulnerabilities and coping mechanisms, did the actual cultivation of land plus and crop husbandry practices. The soil scientists helped during soil sampling, interpreting soil test results and monitoring soil water content. The agriculture extension officer was instrumental in profiling the study site, identifying vulnerabilities, mobilization and providing advisory services on crop management practices. The meteorologist helped to obtain historical weather data, perform weather forecast and interpreting weather trends. The NGO representative aided in profiling vulnerabilities, mobilization and prioritizing coping mechanisms. The main researcher offered coordination of the entire transdisciplinary research, data collection and compilation of this report

3.7.3. To determine the Inter-Seasonal and Inter-Annual Climatic Trends For Wiyumiririe

Historical weather data was acquired from the nearby Lamuria agro meteorological station weather station operated by the Water and Natural Resources Management (WARMA, for KMD Kenya) for the period between 1958 and 2017. The data was therefore more than enough to meet the minimum 30 years needed for credible climatic analysis (WMO, 2009). Two meteorological indices were calculated for analysis of rainfall data. Rainfall Anomaly Index (RAI) was calculated to determine inter-seasonal rainfall trend, variability and intensity and Analyze severity of drought and wetness during the main (March -July) cropping season and the short (October -December) cropping season respectively. Standardized Precipitation Index (SPI) was calculated and run to analyze history and severity of both drought and wet years. Rainfall Anomaly Index was developed and subsequently used by Rooy (1965).

$$RAI = +3\left(\frac{RF - M_{RF}}{M_{H10} - M_{RF}}\right)$$

$$RAI = -3\left(\frac{RF - M_{RF}}{M_{L10} - M_{RF}}\right) \qquad \ldots\ldots 4$$

Source. Ayansina, et.al., 2017

It is calculated based on two equations for positive and negative values respectively. Where: RF is the total amount of rainfall for the year in reference, MRF is the mean seasonal rainfall for the entire period: MH10 and ML10 are the mean of the ten highest and lowest values for RF (Ayansina et. al., 2017). Rainfall Anomaly index values that exceed 4 indicate an extremely humid season. Values in the range 0 to 2, means a humid season and between 2 and 4, very humid. On the opposite site of the spectrum, values of between 0 and -2 are for a dry season, -2 to -4 very dry season and below -4 extremely dry seasons Table 3.2 shows the classification of seasons based on RAI values.

Table 4: Classification of Rainfall Anomaly Index Intensity

	RAI range	Classification
Rainfall Anomaly Index	Above 4	Extremely humid
	2 to 4	Very humid
	0 to 2	humid
	-2 to 0	Dry
	-4 to -2	Very dry
	Below -4	Extremely very dry

Source: Freitas (2005)

The standardized precipitation index is an indicator how observed rainfall deviates from a predetermined rainfall probability function that simulates the raw precipitation data. Ordinarily the raw rainfall data are fitted into a gamma or alternatively to a Pearson type III distribution, from which it's transformed to a normal distribution; It was developed by researchers at Colorado State University (McKee et.al., 1993) to quantify rainfall deficit for various time intervals, which are indicators for drought (Ahmad et al., 2016).

Calculation for SPI is based on the long-term precipitation record for a particular location and long-term period (usually longer than 30 years). The computation is illustrated in equation 5.

$$SPI = \frac{X_{ik-\overline{xi}}}{O'_i} \quad \ldots\ldots 5$$

Where, $O_{'i}=$ Standardized deviation for the i^{th} station

$X_{ik}=$ Precipitation for the i^{th} station and the K^{th} observation

$x_i=$ Mean precipitation for the i^{th} station

The SPI computations can be done for various time scales as well as for degree of drought and wetness for study. For this study, SPI values were calculated for 12 months between January 1958 and December 2017. The SPI values are taken to indicate the number of standard deviations by which the observed rainfall anomaly deviates from the long-term mean (Opiyo et al., 2015).

The positive values represent wet periods while the negative values reflect dry periods as provided by Bordi, et.al, (2001) (Table 5). The SPI had successfully been used in Turkana region of Kenya (Opiyo, et. al., 2015), Puruiya District, West Benga, India (Maumita and Biswas, 2013) and Australia (Abawi, et.al., 2003) primarily to examine drought intensity. The SPI has benefits in that it gives better results without other climatic parameters (Pai, et al., 2010). Those benefits notwithstanding, its inability to account for evapotranspiration and intensity of rainfall coupled by its high sensitivity to quantity and reliability of data used to fit to the distribution makes it less attractive in studying the effects of runoff and availability of water in a given system. Table 5 shows the classification of dry and wet years based on Standardized Precipitation Index values

Table 5: Values for Standardized precipitation index

Standardized Precipitation Index range	Description
>2.0	Extremely wet period
From 1.5-1.99	high wet season
From 1.0-1.49	Mildly wet year
From -99 -0.99	Approximately normal year
From -1.0 - 1.49	Severely dry year
From -2.0 and less	Extremely dry

Source Ahmad et al., 2016

In the current study, SPI and RAI were used to examine weather trends, severity of drought and wetness and how that trend mirrored with what the farmers said about Climate Change and Variability.

In the second part, the study downscaled climatic data for the study site using MarKsim^{R}Sim weather generator, for IPCC representative concentration pathways RCP 6.0 derived from an average of 17 Global Circulation Models of CMP5 for the period between 2010 and 2068. The benefit of this tool is that it does not require daily weather data from a meteorological station: Secondly, the user can select the most appropriate representative concentration pathway and the number of Global Circulation models. In the third part, the downscaled precipitation data was used to generate scenarios for future weather conditions.

3.7.4. Calibration and validation of Aquacrop model for growing Sorghum under rain-fed agriculture at Wiyumiririe

3.7.4.1. Introduction

In this section the method for calibrating and validating Aquacrop model is described. In the first part, the experimental design, field layout and administration of treatments are described. In the second part, the process of carrying out calibration and validation is described.

3.7.4.2. Field Layout and Experimental Design

The study site was a 100ft by 100ft piece of land located within Shalom (D) village (latitude -0.7889: longitude 36.656). The land was donated by one of the farmers involved in the exploratory research. Given that Sorghum has been calibrated and validated by FAO and the information is available in Aquacrop data base, calibration for this study entailed describing the environment and making adjustments to non-conservative crop parameters. To calibrate and validate Aquacrop model necessitated establishment of field trials that run between January 2016 to February 2019 capturing in both long and short rainfall seasons. The experimental plot was set up in a split-plot design where double digging, Zai pits and conventional farming were the main factors whereas the varying levels of farmyard manure was the minor factor. The basis for choosing the split plot design was because it allowed investigation of the main factors (Double digging, Zai pits and Conventional farming), minor factor (levels of farmyard manure) and their corresponding interactions. Moreover, the design permitted more efficient application of treatments thereby increasing precision. The site was cleared from vegetation and subdivided into three equal portions. On one section, land preparation was done by double digging, the second portion by constructing Zai pits and the third portion cultivated normally. To cater for the five manure levels of treatment replicated twice, the portion under double digging was subdivided into ten equal portions measuring 8m long and 0.6m wide. In double digging, individual portions were further subdivided into four equal parts labeled 1 to 4. Portion 1 was dug to 30cms deep and soil pilled adjacent to it. Then by use of a pitchfork the remaining subsoil was loosened another 30cms deep. Portion 2 was dug next, back filling the previously dug portion one but after mixing with farmyard manure as per respective application levels. The process was repeated to dig up portion three and four. The piled up soil from portion 1 was eventually used to fill up portion 4. There were four levels of farmyard manure applied (5tons/ha, 3.75tons/ha, 2.5tons/ha and 1.25tons/ha) and the unfertilized control (With no manure application) which together constituted the five treatments. On the portion reserved for construction of Zai pits, pits were demarcated and dug. Each pit measured 60cm by 60cm wide and 60cms deep. The distance from one pit to the other within the row and between rows was 60cms. In total 100 pits were made and by random sampling technique, the five treatments were administered. Likewise, the portion under conventional farming was divided into ten portions, where each treatment was randomly administered, twice per treatment. To administer the treatments in Zai pits, a 20kg bucket was used to measure the quantities of farmyard manure commensurate to each application rate. For each Zai pit where manure was applied, it was first mixed with soil from that pit and the mixture used to fill up the same pit forming a homogenous layer, 60cms deep. In the portion where double digging was carried out, a 2kg container was used to measure manure. To do that, planting holes (60cms deep) were made. Manure of appropriate quantities was mixed with soil two weeks before sowing and the planting holes refilled with the mixture. No manure was applied in the unfertilized control both in double digging and Zai pits. In subsequent planting seasons the amounts of farmyard manure applied was adjusted to cater for residual effect. Figure 9 shows the split plot design.

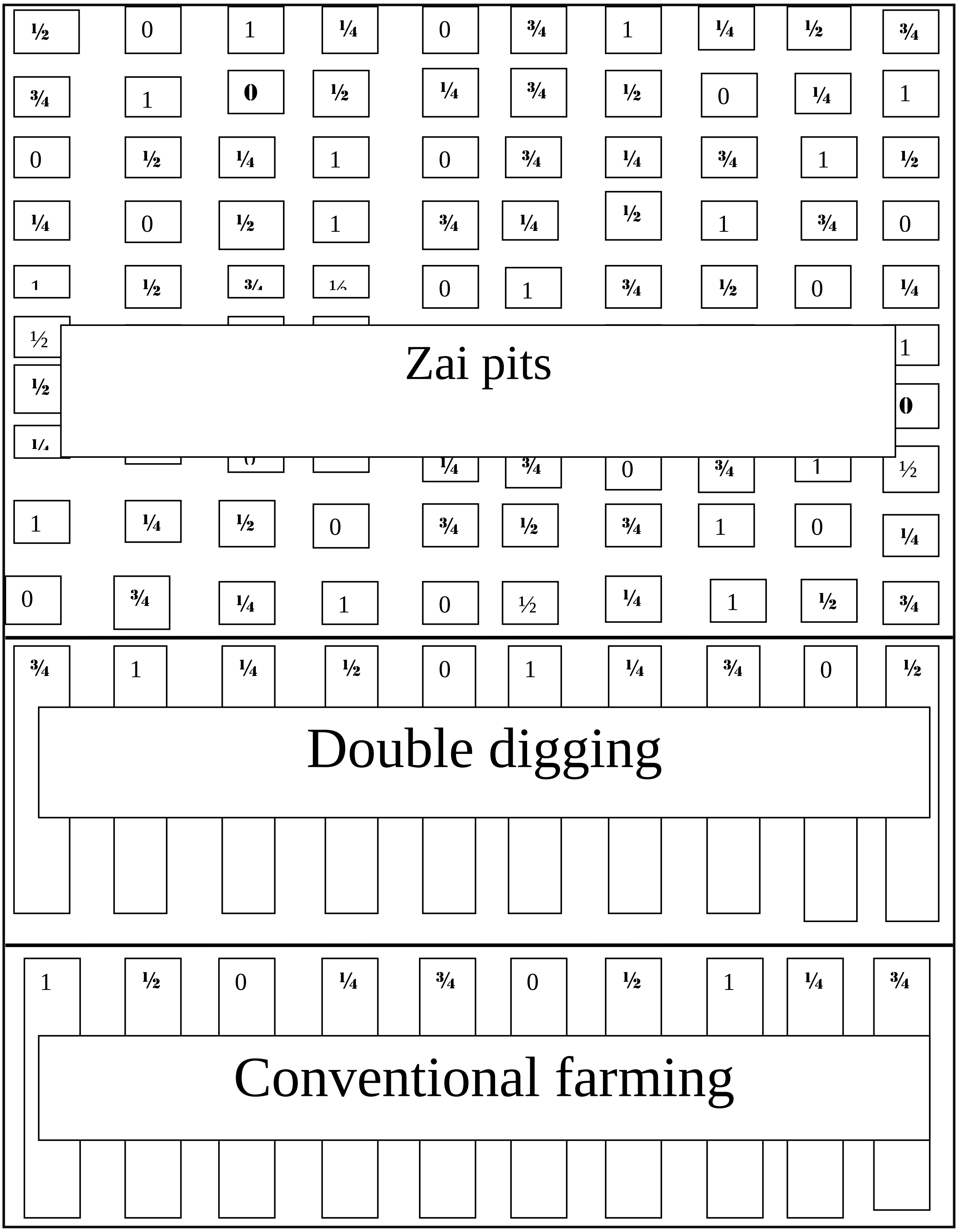


Figure 9: The Split Plot Experimental Design**.** Where, 1 represents 5tons/ha, ¾(3.75tons/ha), ½(2.5tons/ha, ¼1.25(1.25tons/ha and 0 no manure /unfertilized control.

3.7.4.3. Aquacrop Model Calibration and validation

The calibration and validation process was run using Aquacrop version 6.0 and involved tuning the non-conservative crop parameters for the environment in which the crop was cultivated; i.e. adjusting the assigned values in Aquacrop to match with field observations taken at Wiyumiririe without altering the default values for conservative parameters. Seredo variety of sorghum was cultivated. Its crop development was found similar to the calibrated Bushland Texas available in Aquacrop data base. Calibration was done using data from 2016/2017 cropping cycle while validation was done using data from the 2018 cropping season. The study mainly focused on three parameters; soil water content, canopy cover development and aboveground biomass production. The process of calibration followed trial and error approach as suggested by the developers of Aquacrop (Hsiao et al., 2009; Rae's et.al., 2012). Acceptable pattern of parameters were obtained by adjusting parameters within practical physical ranges. Soil parameters were calibrated first using the default crop parameters for each treatment. That done the created crop file in Aquacrop was tuned taking into consideration soil fertility stress, to reflect the observed parameters as close as possible. Eventually, the model was run to simulate water balance for each of the treatments. Calibration was done in calendar days and not in growing day degrees (GDD) since there was no risk of heat or cold stress. The process of calibration was stopped when good correlation was established between observed and simulated results. This was followed by another cropping cycle to validate the process using experimental data obtained from the 2018 cropping.

3.7.4.4 Climate Data.

Climate data was of two categories; observed and generated weather data. The observed weather data was used for model calibration and validation while generated data was used for simulating future sorghum crop yields. The daily observed weather data was for the period January 2016 to February 2019, while daily generated data was for the period January 2016 to December 2068. It was downscaled for the site using MarKsim^{R}Sim weather generator, for IPCC representative concentration pathways RCP 6.0 derived from an average of 17 Global Circulation Models of CMP5. Consequently, there were two climate files; Observed weather data file and generated weather data file. The Climate file (CL) contained the rainfall file, Tnx file (for maximum and minimum air temperatures), Eto file containing the daily reference evapotranspiration and, selected representative concentration pathways (RCP) files sourced from Aquacrop data base. The respective, rainfall, temperature files contained daily data for study period observed and downscaled. These parameters together with daily values for relative humidity, solar radiation, and wind speed plus station characteristics were used to calculate daily reference evaporation using the built-in ETo calculator.

3.7.4.5. Soil Profile Characteristics

To describe soil water retention and movement, Aquacrop requires an initial determination of soil textural class; soil water content at saturation (SAT) field capacity (FC) and permanent wilting point (PWP) plus hydraulic conductivity (Ksat). To achieve that, representative samples from each treatment were taken to Kenya Agricultural Organization soil laboratories Kabete, Kenya for analysis. The results formed the input data for mode calibration and to derive other parameters; capillarity rise; Drainage Coefficient (tau); Curve Number (CN) for determining surface run off; TAW- Total Available Water, which determines the size of water reservoir and REW- Readily Evaporative Water, for calculating the rate of soil evaporation. Since there were three parcels of land prepared differently with varying levels of farmyard manure, the soil profile characteristics varied accordingly prompting this study to generate input soil file for each treatment. To calibrate soil water content, soil samples from each treatment were chosen randomly every two weeks at a uniform depth of 15cms and analyzed for soil moisture content by gravimetric method.

The procedure of determining soil water content at the root zone involved four steps: Calculating; mass percentage of soil water, volumetric water content, equivalent depth and soil water content at the root zone.

To calculate the mass percentage of soil water, samples of soil were weighed to get the mass of solid plus water.

(M_{S+W}}=Solid and water ……………………………………………………………….....6

Where; Ms is mass of solid and Mw is mass of water.

The soil samples were then put in a ventilated oven set at 107^0c for 24 hours during which all water evaporated. The samples were weighed again to get the weight of solid. The mass water content was obtained by dividing the mass of water by the mass of the soil solid.

$$\theta_m = \frac{m_{s+w} - m_s}{m_s} = \frac{m_w}{m_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

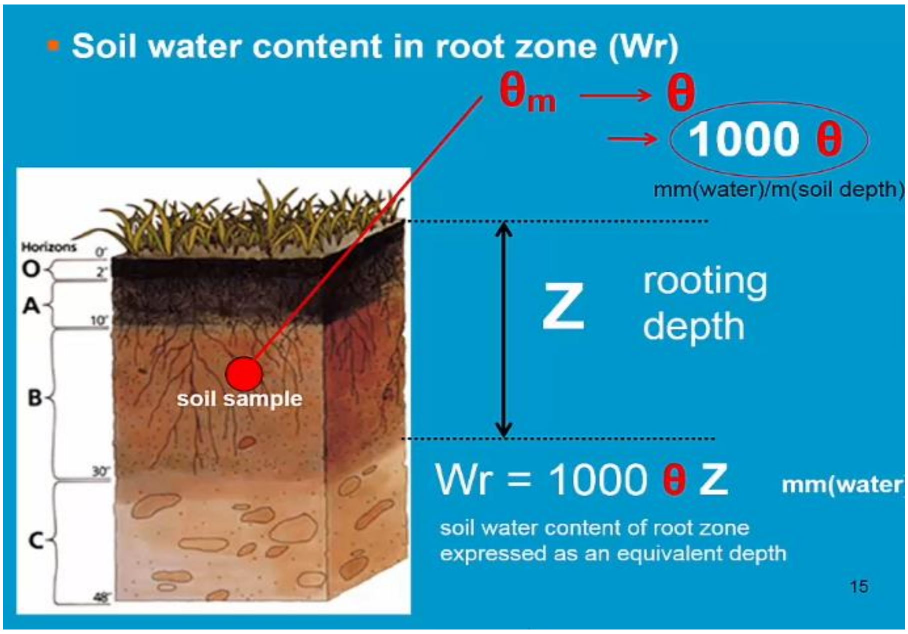
To express the mass of water in volumetric water, the soil water content was calculated by multiplying the mass percentage of water by the ratio of bulk density of the soil to that of water.

$$\theta = (p_b/p_w)\theta_m$$

$$p_b = \frac{mass\ dry\ soil\ (m_s)}{bulk\ volume\ soil\ (DA)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

The equivalent depth defined as the ration of depth soil water to that of the whole soil was calculated by multiplying the obtained volumetric water content by 1000. The results were expressed in millimeters of water per meter of soil depth i.e. (mm)/m.

Finally, the soil water content at the root zone was determined by multiplying equivalent depth by the rooting depth (0.60m). The values obtained were entered in the Aquacrop software as field data.



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Results for soil water content measured from the field at two weeks interval was fed into the model to simulate soil water balance during the entire growing cycle as determined by rainfall, soil evaporation, capillarity rise and deep percolation. The process was repeated in subsequent cropping cycles until some level of consistency was established. Since cultivation was done at a uniform depth of 60cms, the same depth was taken to be the effective rooting depth. The curve number (CN=72) which determines surface runoff and soil evaporation (REW=11) were adopted as assigned by the model. Saturated hydraulic conductivity values were those determined from laboratory analysis while ground water table was set at varying as observed during the growing cycle. NB: To monitor ground water table, a circular pit (diameter 30cms and 4meters deep) was dug between the main plots and measurements done at regular intervals.

3.7.4.6. Crop Parameters and Yields.

The default conservative crop parameters values found for sorghum as calibrated for Bushland Texas 1991 were taken for initial creation of respective crop files. The crop parameters that were specified during model calibration were: planting density, crop establishment i.e. time to 90% emergence, maximum canopy cover and days to maximum canopy cover and time to flowering and duration of flowering, start of yield formation and days for building harvest, time for onset of senescence and reaching physiological maturity and Harvest Index (HI) for all treatments. Calibration for soil fertility entailed making qualitative assessment of the canopy development then assigning values through trial and error. The complete nutrient analysis done before the onset of the growing cycle acted as a guide.

After loading the climate file for Wiyumiririe, this study created Sorghum crop files per treatment for subsequent updating in Aquacrop model. Sorghum seeds were directly sowed in shallow holes at depth of 25mm beneath the soil surface at a spacing of 40cms by 30cms giving an approximately plant density of 83,333plants/ha. Germination of seeds was characterized by coleoptiles protrusion above the surface level which was followed by weekly monitoring and scoring to record the time for 90% emergence. Thinning was done within 2-3 weeks of germination so to attain the correct plant population. The size of the germinating sorghum seedling is a conservative crop parameter and the same value ($5cm^2$) was used to calculate the initial crop development when approximately 90% of the seedlings had germinated (CC_o=0.4167%). I.e. CC_o=Plant density multiplied by canopy cover size for individual seedlings.

To monitor crop growth, field observations were done at two weeks interval for percent canopy cover, aboveground biomass production and soil moisture content. To estimate percent canopy cover, 20 digital photographs/treatment were taken every fourteen days at a perpendicular height 1.5meters above the crop using Canopeo software installed in an IPod. The software automatically calculates the average percent canopy cover. The output values were entered into the Aquacrop model. The time and maximum canopy cover was determined when no increment was noted in percent canopy cover. The time to flowering estimated from the day of sowing was recorded when almost 50% of the plants per treatment showed exposed anthesis. To determine biomass production, above ground parts of four representative plants from each treatment were collected through destructive sampling and analyzed for dry matter content. Plant samples were first oven dried for 24hrs then weighed. The resulting weight was multiplied by plant density to get dry matter in tones/ha. To determine maximum effective rooting depth selected plants were carefully uprooted at maturity and measurements made for the rooting depth. The yields were obtained by harvesting panicles from10 plants selected randomly from each treatment. The time to harvest was determined when the grains were hard in a way that they didn't produce milk when pressed between fingers. Threshing followed to separate grains from panicles after which the grains were oven dried at 70^{o}C for a period of 48hours. The average weight per panicle was multiplied by the planting density to give the yields in tons per hectare. To determine Harvest Index (HI) average yields were divided biomass at harvest time.

3.7.5. Evaluation of simulated results and simulating crop yields under future climatic scenarios is described.

3.7.5.1. Introduction

In this section the method for evaluating Aquacrop model based on the results and simulating sorghum crop yields for current and future weather conditions is described. The section is divided into two parts accordingly.

3.7.5.2. Evaluation of simulated results

The purpose for this was to evaluate simulated verses observed results for the three parameters considered for this study namely; canopy cover, biomass and soil water content. Aquacrop has five inbuilt statistical indexes that were employed;

One: The Pearson Correlation Coefficient (r) is a measure of how two variables relate along a linear line. The values are in the range of -1 to +1. The values that exceed zero indicate a positive relationship and vice versa

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{N}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{N}\right)}} \qquad \text{..........10}$$

Where,

N=The number of pairs of score
$\sum XY$=Sum of product of paired scores
$\sum X$= Sum of X scores
$\sum Y$= Sum of y scores
$\sum X^2$ =Sum of squared X scores
$\sum Y^2$ = Sum of squared Y scores

Two: The root mean squares (RMSE) measures how much simulated and observed values differ. The values vary from 0 to positive infinity. The smaller the value the better the agreement

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(p_i - o_i)^2}{n}} \qquad \text{..........11}$$

Where,

N= The total number of observations
P_i = The predicted values
O_i = The observed values

Three: Normalized Root Mean Square Error CV(s), measures the differences between predicted and observed values. The values are always above zero with lower values indicating a less residual variance, thus a better fit.

$$NRMSE = \frac{RMSE}{\bar{O}} \qquad \text{..........12}$$

Where, O-bar is the average of observed value

Four: The Nash-Sutcliffe model efficiency coefficient (EF), measures how much the inconsistent observed values are accounted for by the model. The values range from negative infinity to one. Value of one (1) is a pointer to a perfect match between simulated and observed data. A value of zero shows that the simulated values are very close to the mean of observed values, while an efficiency value of less than zero shows that the mean of observed data are better than those simulated.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(OBS_i - SIM_i\right)^2}{\sum_{i=1}^{n}\left(OBS_i - \overline{OBS}\right)^2}$$ ……………………………………………………………..13

Where, OB_{Si} is the observation value, SI_{Mi} the predicted value and OB_Sbar refers to average of the observed values.

Five: The Willmott index of agreement (d) measures how close simulated results approach the measured results. The values range from 0 to 1. Values close to 1 indicate a good agreement while those towards zero indicating poor agreement.

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad , \qquad 0 \leq d \leq 1$$ ……………………………………13

Where, O_i refers to the observed value and P_i is the predicted value. Obar refers to the average of the observed values and Pbar is the average of the predicted values.

3.7.5.3. Simulation for Current and Future Weather Conditions.

Studies on the application of crop model in Climate Change, crop development are widely documented. Some rely on perturbation of the observed climate while others depend on direct and indirect weather data to generate outputs that forms inputs for the model. In this study, Aquacrop model was run to determine the expected changes on yields and for the projected future weather conditions for the period 2010-2068. Assuming the status quo to remain in terms of: plant density, growing cycle, crop parameters, soil profile characteristics, field management, depth of ground water table, simulations were carried based on IPCC Representative Concentration Pathway 6.0 emission scenario. The remainders of the IPCC RCP scenarios (RCP 2.6; RCP 4.5; and RCP 8.5), were sequentially selected from carbon dioxide concentration files found in Aquacrop to derive outputs at ten years intervals. Previous study, (Sultan 2013) had shown that there was insignificant increase in sorghum yields from Co_2 fertilizations. However since each IPCC emission scenario represents different storylines that are not necessarily tied to carbon dioxide concentration the need to consider other emission scenarios was vital. Besides, Aquacrop crop simulates the combined effect; i.e. the effects from increased carbon dioxide concentration and altered weather patterns.

3.8. CSA Data Analysis

To prioritize CSA adaptation options the study analyzed results by pair-wise ranking and multi-criteria analysis. Focus group discussion and interview with key informants were analyzed using MAXQDA version 18. Historical precipitation data was analyzed by use of two meteorological indices, Rainfall anomaly index and Standardized Precipitation Index. The same meteorological indices were used to choose CSA options for adaptation. Observed data for canopy growth, biomass, yields and soil water content, were compared with simulated data using five built-in statistical indexes available in the Aquacrop software.

CHAPTER FOUR: RESULTS AND DISCUSSION

Vulnerability assessment, perceptions about Climate Change by farmers, Impacts to Climate Change and options for adaptation

4.1. Introduction

In this part results and discussion derived from the first objective are presented as follows I. Vulnerabilities of the farmers to Climate Change. ii. Perceptions of the farmers towards Climate Change. iii. Climate -Smart Agriculture Adaptation options. iv. Impact and effects of climate change to agricultural production v. Influencing factors to adaptation. vi. Barriers to Adaptation for the Smallholder farmers of Wiyumiririe.

4.2. Vulnerabilities of the Smallholder Farmers to Climate Change

The findings of the study showed that the farmers were indeed vulnerable to Climate Change which had greatly affected their ability to engage in meaningful agricultural activities to address food security. Problem identification through focus group discussion listed food insecurity, drought and lack of water as their most pressing problems. The other concerns raised were, housing, limited credit facilities, inadequate government support and rising poverty. The resource map (figure 10), shows the spatial distribution of farmland, forests, location of rivers, streams boreholes and other sources of water.

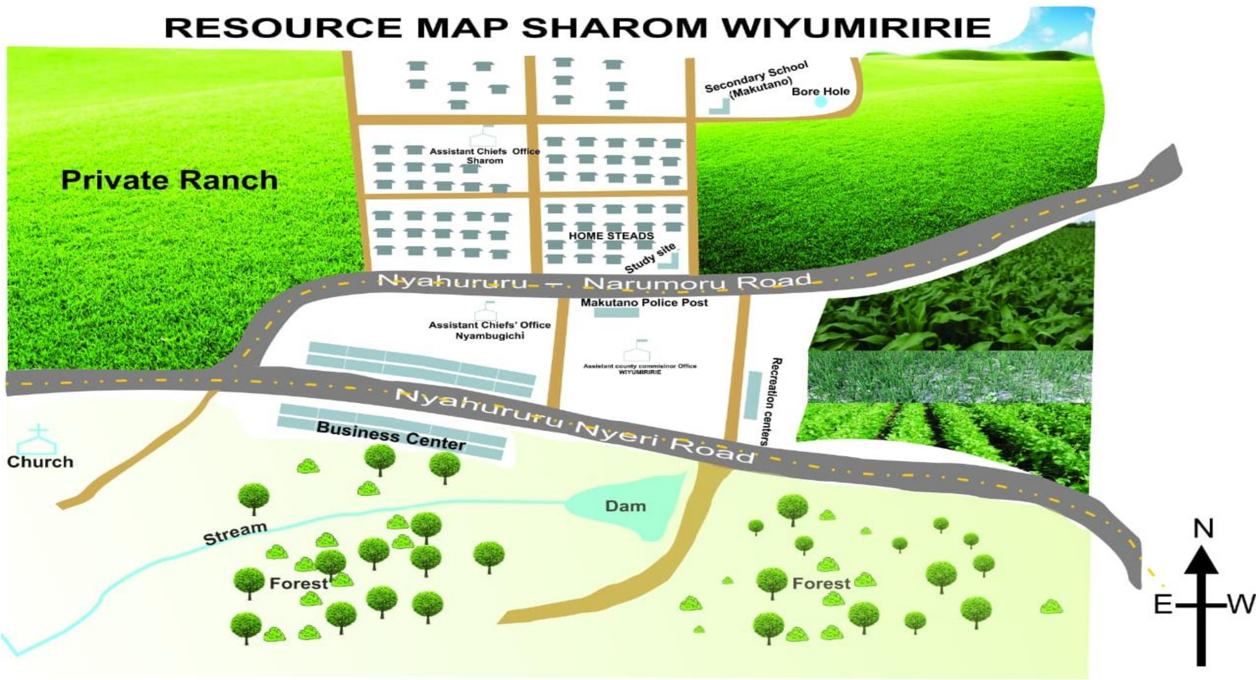

Figure 9: Resource Map for the Study Area

It further shows infrastructure, market, security and administrative offices. The community had three sources of water: a borehole, Suguroi River, and the dam shown. These sources of water were insufficient to meet the water demand for the entire community. Apart from Suguroi River which anyway is far from most households, the other sources were found wanting. The dam is seasonal, occasionally drying out completely during prolonged periods of drought. The borehole was the primary source for clean water serving more than 400 households. Water was not enough to meet the household domestic requirements hence necessitating frequent rationing. With the water deficit meant there was no irrigated agriculture apart from rainwater harvested in water pans. The forest cover was confined along the river banks comprised mainly of acacia woodland, and mostly privately owned. The implication of that was, access and utilization of resources therein was limited. However, because most of the owners were absentee landlords, the Smallholder farmers often took advantage of the situation to collect firewood and graze livestock.

Focus group discussion revealed annual crops grown for food were the most important, with sporadic cultivation of bulb onions for sale. There were two cropping seasons: The (March-July) long rainfall growing season and the (October-December) short rainfall growing season. Based on that, the periods associated with adequate food was during harvest time, August-September and January- February. Still substantial food was expected in the month of June and July from the harvest of potatoes and beans. As per the crop calendar, periods of food insecurity was in the months of March-June and October – November coinciding with the time when crops were ordinarily in the field growing. However, from focus group discussions, it was clear food security did not necessarily follow the crop calendar. Due to unpredictability of rains and subsequent crop failure, periods of food insecurity had, in most occasions lasted the entire year and sometime extending beyond. The months of April and November were listed as the most food secure primarily because the presence of an indigenous vegetable, amaranthus, that often colonizes crop fields few weeks after onset of rains, appeared to spur a variety of diets for many homes.

The climate calendar developed from focus group discussion had a similar pattern to the crop calendar in which participants identified two rainfall seasons: March- July and October – December, long and short rainfall seasons respectively. From focus group discussion, farmers recounted driest years, wettest years and what would constitute a normal year. Participants identified 1984 as the driest year, followed by 2000 then 2016. Similarly, 1997 2003 and

2008 were listed as wet years in that order. Figure 10 summarizes the historical climatic trend line showing how the farmers in focus group discussion provided over a period of 40 years

Crops	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Maize	Harvesting	Land preparation	Planting	Weeding, pest and disease control				Harvesting and land preparation		Planting	Weeding, pest and disease control	
Beans	Harvesting	Land preparation	Planting	Weeding, pest and disease control		Harvesting	No activity		land	Planting	Weeding, pest and disease	
Sorghum	Harvesting	Land preparation	Planting	Weeding, and pest disease control			Harvesting	Addition of manure for the ratoon crop ratoon crop			Weeding, and pest disease	
Onions	Harvesting	Land preparation	Planting	Weeding, pest and disease control		Harvesting	Marketing		Land	Planting	Weeding, pest and disease	
Kales	Raising of seedlings	Land preparation	Transplanting	Weeding, pest and disease		Harvesting and Marketing				Manure application	Harvesting Marketing	
Potatoes	Harvesting	Land preparation	Planting	Weeding, pest and disease		Harvesting Marketing		Marketing	Land preparation		Weeding, pest and disease	

Table 6: Crop Calendar for Wiyumiririe

Source: Focus group discussion at Wiyumiririe

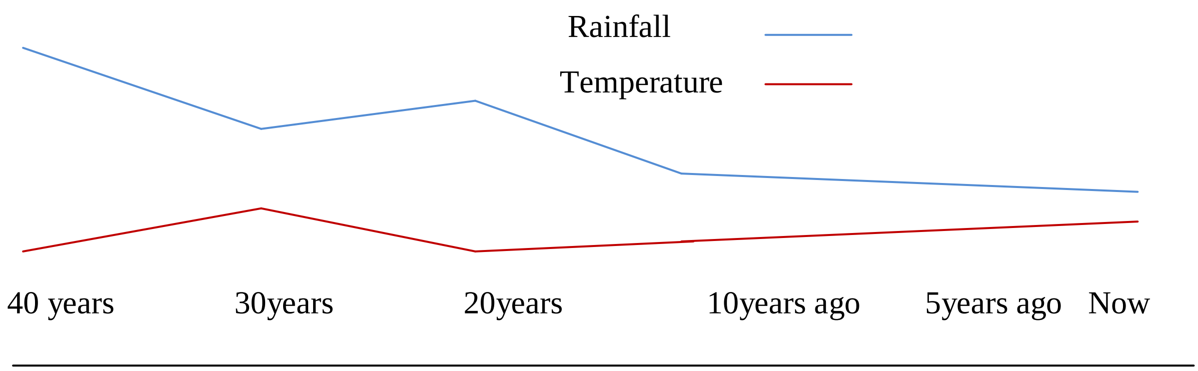

Figure 10: Historical Climatic Trend. (Source. Focus Group Discussion at Wiyumiririe)

According to the farmers, approximately forty years ago, the climate was characterized by high rainfall and low temperatures. However in due course, rainfall declined and temperatures increased. But about 30 years ago the trend change a bit with rainfall increasing gradually and temperatures beginning to fall once again, but around twenty years ago, the trend changed with rains beginning to decline and temperatures rising again, a trend that has persisted ever since.

4.3. Perceptions and Beliefs of Farmers on Climate Change

Results showed that 90% of the farmers were aware of Climate Change and 83.3% believed humans are responsible. The remainder 14% though aware of Climate Change believed its occurrence was by natural processes. Three residents representing 10% of the sample believed climate wasn’t changing, arguing that the place has always been like that. They however pointed out that untrammeled increase in human population coupled by failure to plant more trees was affecting natural water cycle. An overwhelming majority 70% believed Climate Change was a local/regional phenomenon and not global as widely conceived by many literatures reviewed. They acknowledged the weather was changing but the link with increase in anthropogenic greenhouse gases was not succinct. Results from the FGDs (focus group discussion) concurred with what majority of the farmers said, describing Climate Change as a local/regional phenomenon and mainly caused by human activities such as: encroachment to the forest, reckless cutting down of trees, forest fires, charcoal burning and cultivation along river banks. Still some farmers associated Climate Change to an act of God and ancestral curses.

Plate 1: Focus Group Discussion members at Wiyumiririe discussing CSA options.

The findings of this study were almost similar to studies done elsewhere. For instance Grimig et.al., (2013) observed that unlike the American public, farmers in the state of Indiana were less likely to believe in anthropogenic gases as the main contributor to global warming with 79% associating it to natural processes. Similarly Arbuckle et.al.,(2013b) observed that a paltry 8% of Midwestern corn farmers in USA were in agreement that climate change was as a result of human induced activities compared to 49% of the American citizens (Leiserowitz, et.al.,2013).

Additional findings from FGDs indicated that majority of farmers pointed inadequate infrastructure, such as irrigation, improved seeds, and credit facilities to support adaptation influenced their perceptions about climate change. Accordingly these findings were in congruent to a previous study done in Australia in which perceptions of farmers to Climate Change were found to be influenced by presence of infrastructure to support adaptation (Meredith and Nathaniel, 2016).

Table 7: Perception and Beliefs of Farmers on Climate Change (N=30).

Belief typologies	Number	Percentages
Perceptions that climate is changing and it's a global phenomena	6	20
Perceptions that climate is changing but it's a local phenomena	21	70
Perception that climate is changing and humans are responsible	25	83.3
Perception that climate is changing and humans are not responsible	2	0.067
Perceptions that climate is not changing and humans contribute to Climate Change	2	0.067
Perceptions that climate is not changing and humans do not contribute to Climate Change	1	0.033

With regard to rainfall, 90% of the respondents reported a decrease in the total amount. Others reported that onset of rains had changed greatly with the long rains delaying, and then breaking early before crops had reached physiological maturity. Consequently, crop failure had become the norm rather than the exception. Eighty three percent (83%) of the respondents reported short rains were more predictable compared to the main March-July rains, views that were collaborated by the FGDs. The challenges were that at times, the short rains came unusually too early before they had prepared land. A proposal to consider the October -December to be the main cropping season was inconclusively discussed.

On temperatures, 70% of the farmers believed temperatures had increased, 23.3% had reduced, 0.03% believed temperatures hadn't changed while the remainder 0.03% didn’t know whether temperatures had changed or not.

Table 8: Farmers’ Perceptions about Weather Trends

Belief typology	% Respondents (n=30)
Rainfall had increased	0.03
Rainfall had decreased	90
Rainfall had remained the same	0.03
Do not know whether rainfall had increased or decreased	0.03
Onset of long rains had changed	93.3,_comes late
Onset of short rains had changed	66.7 comes early
Temperatures had increased	70
Temperatures had decreased	23.3
Temperatures had not changed	0.03
Do not know whether there had been any changes on temperatures	0.03

4.4. Impacts and effects of Climate Change to the Agricultural Production

The various stakeholders mostly concurred in opinion with regard to the impacts of Climate change to agricultural production. Individual farmers, key informant and FGDs indicated Climate Change had impacted negatively to the Agriculture sector in a number of ways. Seventy four percent of farmers reported crop failure due to erratic and inadequate rainfall. In three out of five years, farmers indicated they hadn't received any harvest. For instance, between January 2016 and February 2018, only one cropping season was successful for farmers who employed conventional cultivation methods. Consequently crop and livestock production activities were adversely affected making it hard for the farmers to attain food security. In a few isolated cases, farmers reported an increase in crop pest and diseases, but the study was unable to associate that to Climate Change.

Remarkably 82% of farmers who had been there for more than 30 years reported an increase in the incidences of frost in the months of January which they attributed to Climate Change. Arable and pasture crops were the main casualties in form of frost bite. As a result, the affected crops did not recover afterwards exacerbated by dry spells that are common in the months of January. From the FGDs, reports indicated an increase in hailstones, during the months of July and November that caused huge crop losses. Flash floods were adversely mentioned that caused soil erosion, and uprooting of crops on sloppy areas in the month of

April. With the food aid from government and well-wishers having stopped, majority of the households were dependent on off-farm income to make ends meet.

Table 9 : Extreme weather events for Wiyumiririe

Climatic variable	% Respondents(n=30)
Unpredictable weather pattern	80%
Prolonged dry spell/drought	90%
Increase intensity frequency of hailstorms	83.3
Flash floods	86.7
Increase in intensity and frequency of frost	90

According to reports from key informant interviews these Climate Change associated hazards, greatly undermined the capacity of the residents to produce enough crop yields to meet their family food requirements. The compounding effects of poverty and lack of infrastructure to support adaptation were triggers to social economic and psychological problems. Divorce, family feuds and community infighting had intensified. As some family members left home to seek off -farm income, a number of those left behind were accused of engaging in extramarital affairs in exchange for food and scouting for food in funeral and wedding ceremonies where it was guaranteed. Balanced diet was an alien concept and animal sources of protein considered a luxury. The findings of this study to a great extent agrees to a previous one done in Lawra district of Ghana where Climate Change was found to cause social economic and psychological problems to farmers (Ndamani and Watanabe, 2015).

That has a bearing to this study because climate change caused secondary effects as discussed. For that reason, the policy makers at Wiyumiririe require to be vigilant so that social economic and psychological problems highlighted are addressed. This is because if left unattended to, the effects are likely to undermine the adaptive capacity of the residents with far-reaching consequences to their food security and resilience to change.

In the face of aforementioned impacts, farmers in FGDs and feedback from key informants reported using a variety of primary adaptation strategies which included: use of water pans to irrigate vegetables in the kitchen gardens, change in planting date, use of drought escaping crop varieties, rearing of indigenous poultry and use of farmyard manure to conserve soil moisture and address soil fertility.

4.5. Climate-Smart Agriculture Adaptation Options Prioritized For the Study Area

In this section, results of the identified and prioritized Climate-Smart Agriculture options are presented. The process was carried out using Multi-criteria analysis during iterative meetings with all stakeholders. In the same forum, weights and scale for criteria and options used were agreed upon. Pair-wise ranking for the different categories of stakeholders preceded that.

Table 10: Multi-criteria Analysis for selecting Climate-Smart Agriculture Options

	Criteria						Score	Rank
Options	Capacity to increase crop yields	Capacity to withstand dry spell	Financial feasibility	Legal and political feasibility	Capacity to improve soil fertility	Speed of implementation		
Improved maize variety in Zai pit	3	3	3	3	2	2	2.65	6
Improved maize variety in Double digging	3	3	2	3	3	2	2.60	7
Indigenous Sorghum variety in Zai pit	3	4	3	3	3	2	3.3	4
Indigenous Sorghum variety in Double digging	3	4	3	3	3	2	3.3	4
Improved maize variety in Zai pits plus farmyard manure	4	4	4	3	4	1	3.6	2
Maize variety In double digging plus farmyard manure	4	4	4	3	4	1	3.6	2
Seredo sorghum variety in Zai pits plus Farmyard manure	5	5	4	3	4	1	4.1	1
Seredo Sorghum variety in Double digging plus farmyard manure	5	5	4	3	4	1	4.1	1
Improved maize variety plus change in planting date	3	3	3	3	3	4	3.1	5
Indigenous Sorghum variety plus change in planting date.	3	4	3	3	3	4	3.35	3

Taking the discussion to the criteria, capacity to increase crop yields and to withstand dry spell were given the highest weight (0.25 each). Food security and inadequate rainfall were unanimously agreed as most important issues requiring attention. Next was financial feasibility with a weight of 0.15. Majority of farmers are resource poor, depending on family labor to cultivate land and using previous season's harvest as source of seeds for the subsequent season. Without access to any form of credit to finance adaptation options, finances were of primarily concern to them. Soil fertility was equally important to all hence a weight also of 0.15. Accordingly, any measure to address food security as majority of the participants said, need to take into account soil fertility. Fatigued from receiving food donations which by the way had become irregular, farmers attention had shifted to growing their own crops, a decision that carried the day during iterative meetings. Both political feasibility and speed of implementation had a weight of 0.10, meaning that, adaption measures required conformity to the government regulations, for farming and environmental protection as well as to be implemented rapidly so that benefits could be realized.

All the prioritized CSA options were given a scale of 1-5 in relation to each criterion. From the consultative forum involving all stakeholders, cultivation of Seredo Sorghum variety, on parcels of land prepared by double digging and Zai pits in a field management involving addition of farmyard manure at various rates were the most preferred options. These choices were grounded on the ability of sorghum crop to withstand drought compared to maize. From expert knowledge, double digging and construction of Zai pits were considered more appropriate technologies for harvesting and retaining rainwater at the root zone. Water pans and soak pits were hitherto widely used by farmers as rainwater harvesting technologies. However the technologies were becoming obsolete because of water loss through seepage, evaporation and menacing mosquito breeding grounds. Contrary to expectations, use of improved Gadam drought escaping sorghum variety was not a favorable option as it was said to be highly susceptible to birds attack. Compared to the indigenous variety, the improved varieties were found to contain high concentrations of sugars which made them highly susceptible to birds attack. The ability of indigenous Sorghum variety to tiller and form a ratoon crop was a huge advantage compared to the improved varieties. However their slow growth rate and eventual low yields had made farmers forfeit them.

4.6. Barriers to Adaptation for the Smallholder Farmers

The barriers to adaptation identified most pressing to farmers included; Unreliability of rainfall, long distance to farms, water scarcity, poor soils, lack of suitable drought escaping crop varieties and untimely weather information. Access to agricultural subsidies and high cost of farm inputs were cited as moderate constraints. Inadequate farmers' advisory services, lack of market for agricultural products were found to be less important barriers. The findings of these results were corroborated with FGDs in which erratic and inadequate rainfall, coupled with lack of water resources made it impossible for farmers to employ appropriate CSA practices for Climate Change adaptation. Discussion with FGDs and interview with key informants identified lack of policy framework, conflict of interest between county and national government as pertinent. Generally, similar findings were reported in other studies, (Deressa, et.al., 2011: Bryan et al., 2009: Tessema, et al., 2013: Madison 2007 and Ndamani and Watanabe 2015).

CHAPTER FIVE: RESULTS AND DISCUSSION

Historical Climatic Trends for Wiyumiririe

5.1. Introduction

In this chapter results and discussion derived from the second objective are presented in the following parts. I. Annual and decadal precipitation trends. ii. Rainfall seasonal trend and variability using Rainfall Anomaly Index analysis. iii. Yearly precipitation trends, severity of drought and wetness based on Standardized precipitation index values.

5.2. Historical Rainfall Trends and how they Mirrored With Perceptions of Farmers

The general trend of the rainfall pattern from 1958 to 2017 is presented in figure 11.

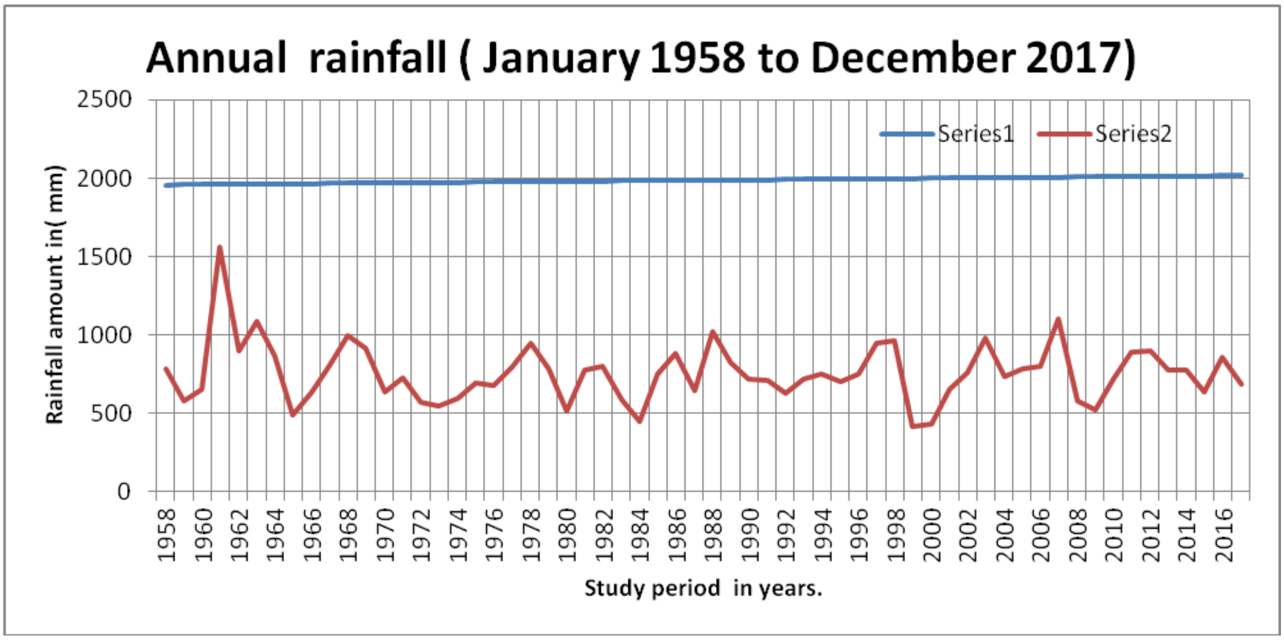

Figure 11: Annual Precipitation from 1958 to 2017

Analysis of annual totals of rainfall reveals a declining trend from 1961 to 2017, with a pick in 1961 (figure 10). Earlier years were characterized by high rainfall, the highest amount recorded (1558.4mm) in the year 1961. The other peak years when rainfall exceed 1000mm was in 1988 (1022.4mm) and in 2007 (1103.3mm) respectively. Respondents who have been farming for more than 30 years cited 1982 to 1984 as the driest periods and 1997-1998 to be the wettest, which did not necessarily correspond with the observed data. The declining amounts of rainfall over the last decade was observed, a phenomena corroborated by farmers in focus group discussions (FGD).

At the same time, the average air temperatures were observed to increase during the 2016 - 2068 period. Therefore, the declining amount of rainfall and increasing temperatures confirmed that climate change is a reality. These findings concur with other studies that predicted declining rainfall for Eastern Africa in the 21st century (Hulme et al., 2001; IPCC, 2001). The findings have a bearing for this study because the associated water and temperature stress to sorghum crop will lead to a reduction in yields hence, exacerbating food insecurity for the residents.

Figure 12 shows the Aquacrop model output for maximum and minimum air temperatures for the period (2016-2068).

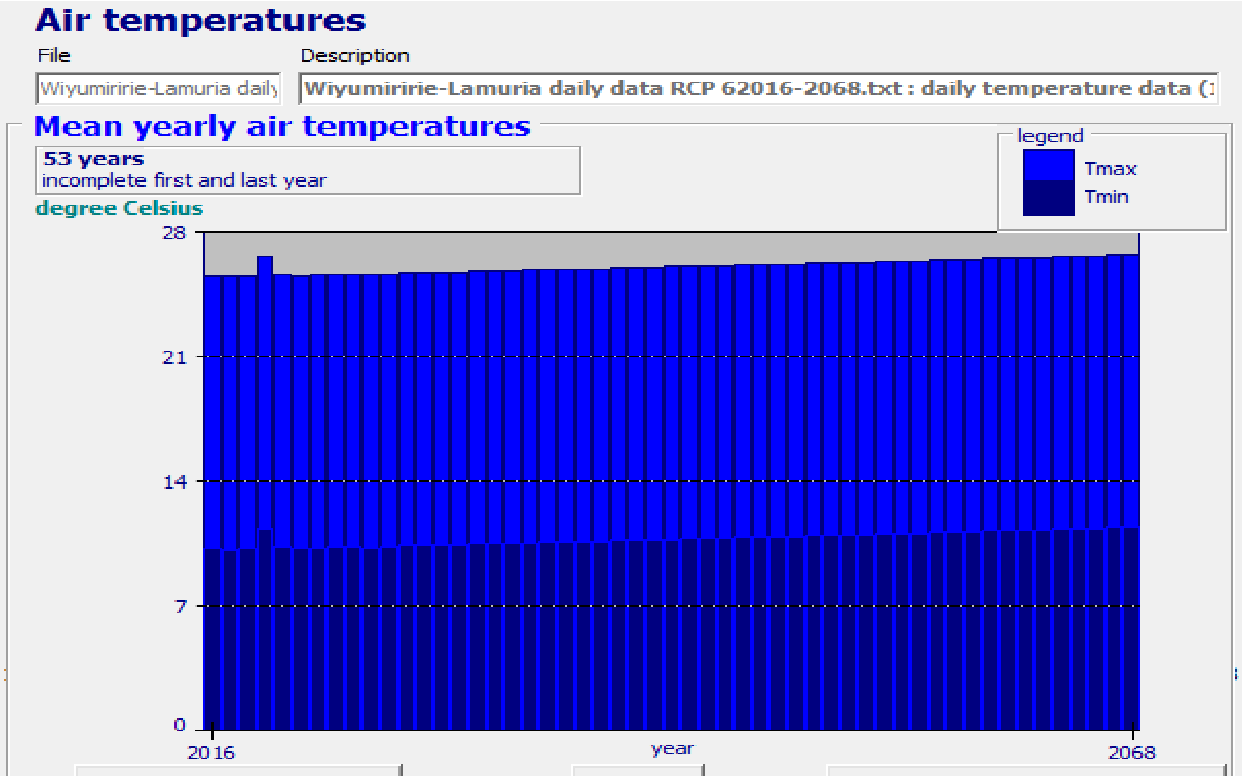

Figure 12: Projected maximum and minimum air temperatures

5.3. Rainfall Variability and Anomaly during the Long Rainfall Season [March-July]

Results showed great variability in rainfall during the (March-July) long rainfall growing season for the 60 years under review (Figure 14). The very humid seasons occurred in the years: 1968, 1988, 1997, 1998, 2002, 2003 and 2007 with respective rainfall anomaly indices of: 3.812, 3.136, 2.8, 2.495, 3.141, 3.278 and 3.673. Henceforth, it was accurate to infer that only seven out of sixty years the area received high rainfall. The rest of the years were characterized by average to low rainfall. However the distribution of wet and dry seasons showed half the seasons registering positive RAI values while the other half had negative values. Near normal rainfall for the long rainfall season was received only in three years (1962, 1994 and 1995). However the trend was inconsistent. For instance, 1968 had a very humid season. However, it took another 20 years for the situation to recur in 1997. Between 1997 and 2017, the number of very humid seasons more than doubled, presumably because of the El Nino phenomena during the 1997-1998 seasons.

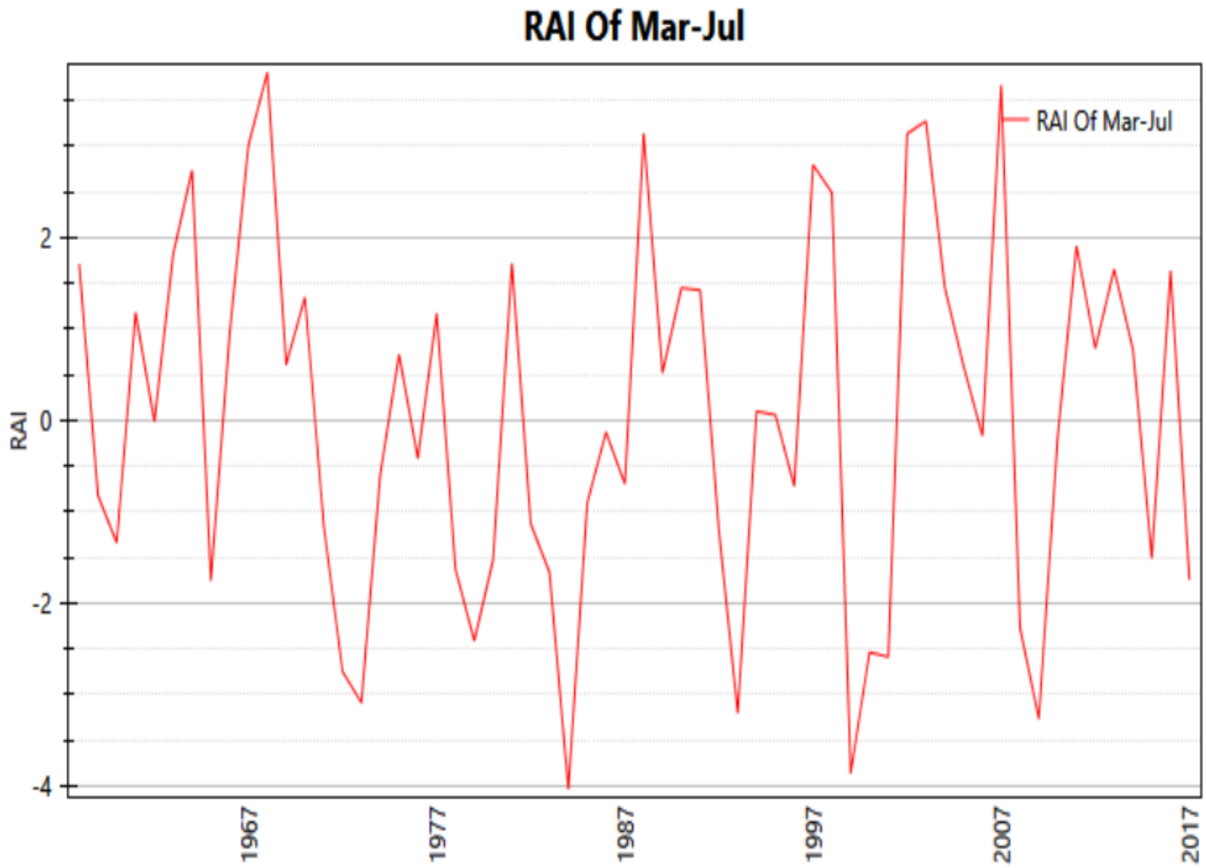

Figure 13: Rainfall Anomaly Index of the March- July long rainfall season (LGS)

Conversely, in spite of an increase in humid seasons over the past 20 years, rainfall has been erratic. Unlike the gradual change encountered between 1968 and 1973, drastic changes were observed beginning 1998. In that year RAI values of was 2.495 (very humid) but the following year 1999, the RAI figure dropped to -3.864, (very dry) signifying a huge reduction in the amount of rainfall during the March-July growing season. The same situation recurred between the years 2007 to 2009 season. The implications of such erratic rainfall pattern was difficulties in making farming decisions; an observation corroborated by farmers in focus group discussion (FGDs) and by key informants.

In total, there were ten dry periods between 1958 and 2017. Four of them lasted for a duration of one year and were generally less severe: In 1960, 366 days (severity 0.348); 1965, 365 days (severity 0.764); 2015, 365 days (severity 0.514) and 2017, 365 days (0.752) Table 12.

Table 11: Rainfall Anomaly Index, the severity of drought for March-July long rainfall season

Number of drought	**Start of drought period**	**Duration**	**Number of seasons**	**Severity of drought**
1	1/1/1960	366	One	0.348
2	1/1/1965	365	One	0.764
3	1/1/1971	1096	Three	4.01
4	1/1/1978	1096	Three	2.593
5	1/1/1982	1096	Three	3.861
6	1/1/1992	731	Two	2.427
7	1/1/1999	1096	Three	6.015
8	1/1/2008	731	Two	3.553
9	1/1/2015	365	One	0.514
10	1/1/2017	365	One	0.752

There were four very long dry spells each extending to 1096 days; i.e. running through three consecutive seasons; 1971 (Severity 4.01), 1978 (Severity 2.593), 1982 (Severity 3.861). The driest year with a severity index of 3.046 was 1984, accounting for the highest proportion (79.4%) of the 1982 drought period. The findings of this study were in tandem with a previous one done by (Shisanya, 1990) which reported a severe drought occurring during the 1983-1984 seasons that compelled the Kenya Government of the day to launch a national wide food relief program. The study investigated the severity of the 1983-1984 drought in Kenya from a climatologically perspective. Rainfall data for the 1983-1984 period was compared to that of other years within a span of ten years. . The study observed that several stations in Kenya had recorded significant rainfall deficits during those two years compared to other years, thereby confirming the period to be the driest

This current study has shown that calculating the severity of drought per year as well as per the period is important. For instance, even though the 1971 drought was more severe (severity 4.01) than that of 1982 (Severity 3.681), the impacts were only mildly felt by farmers because the dry period was spread evenly over three seasons while in 1984 the dry period was mostly concentrated in one season(March-July). The findings also matched with farmers' perceptions about extreme weather events in which they recalled the drought periods of 1984 and1999 respectively, which had left a trail of crop and livestock losses.

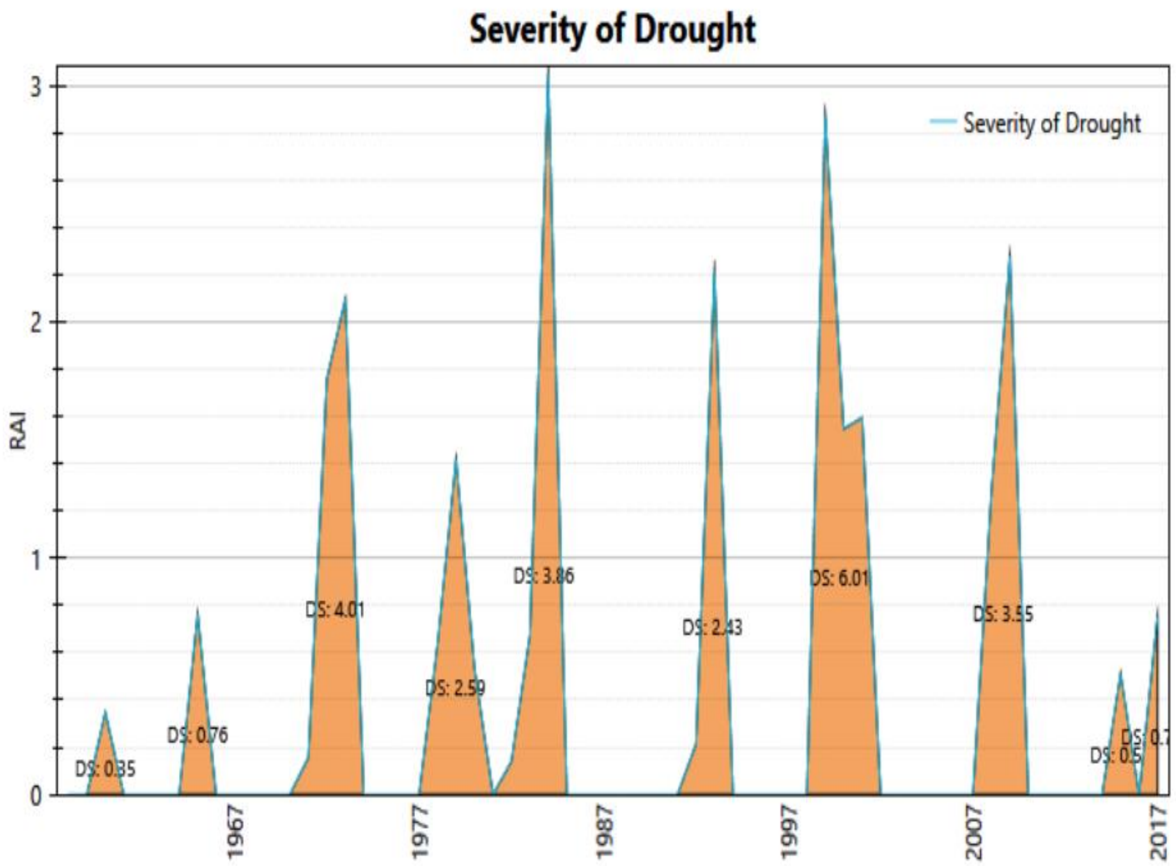

Figure 14: Rainfall Anomaly index, severity of drought of the March-July long rainfall season

With regard to wet seasons, results showed that between 1958 and 2017 they were fifteen of them during the long rainfall season (March-July). The periods beginning March 1958, 1961, 1970, 1977, 1981, 1988, 1990, 1997, 2002, 2007 2011, 2013 and 2016 all had duration of one wet season. Periods starting March 1963, 1967, 1990 and 1997 had about 730 days (two seasons). The wet period beginning March 2002 was the longest because there were three consecutive cropping seasons which also recorded the highest intensity (4.91) as shown in Table 13.

Table 12 Rainfall Anomaly Index, the severity of wetness for March-July long rainfall period

Number of wet period	Start of drought? period	Duration	Number of seasons	Severity of wetness
1	1/1/1958	365	One	0.727
2	1/1/1961	365	One	0.193
3	1/1/1963	731	One	2.582
4	1/1/1967	731	One	4.848
5	1/1/1970	365	One	0.362
6	1/1/1977	365	One	0.186
7	1/1/1981	365	One	0.732
8	1/1/1988	366	One	2.146
9	1/1/1990	730	One	0.9
10	1/1/1997	730	Two	3.315
11	1/1/2002	1096	Three	4.91
12	1/1/2007	365	One	2.683
13	1/1/2011	365	One	0.921
14	1/1/2013	365	One	0.668
15	1/1/2016	365	One	0.653

The wettest seasons occurred in the years; 2007 (severity 2.6825), 2003(severity 2.2875), 2002 (severity 2.1509) 1997 (severity 1.8104) and 1998 (severity 1.5049). These findings are crucial because they show that compared to 2002, 2003 and 2007 seasons, most of the rains that fell during the 1997-1998 periods did not coincide with the traditional March- July growing season despite those years being widely perceived to be the most wet because of the El Niño phenomenon. These results are important to agricultural extension advisory services because they indicate that heavy rains that do not fall within the traditional growing season are not necessarily helpful to farmers. Hence the officers need to be aware of such unique trends and advice farmers accordingly especially with regard to planting dates.

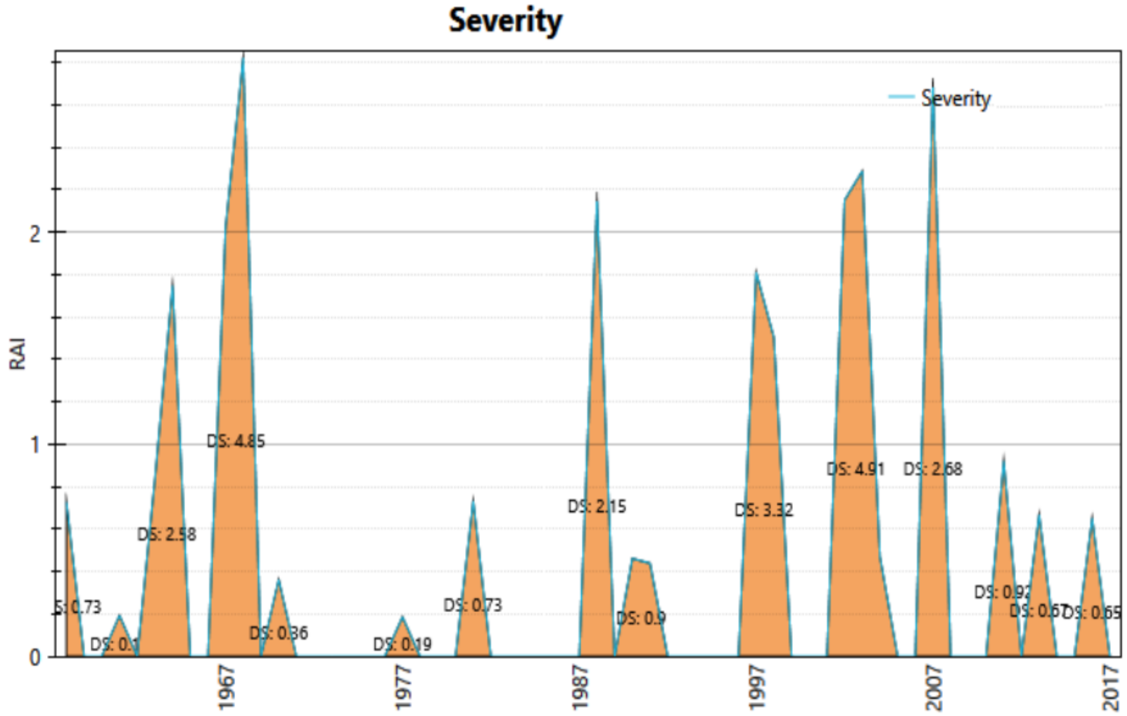

Figure 15: Rainfall Anomaly Index, Severity of Wetness for the March-July Long Rainfall Season

Thirty six years (1959, 1960, 1962, 1965, 1966, 1969, 1971, 1972, 1973, 1973, 1974, 1975, 1976, 1978, 1979, 1980, 1982, 1983, 1984, 1986, 1987, 1989, 1992, 1993, 1994, 1995, 1999, 2000, 2001, 2005, 2008, 2010, 2012, 2014, 2015 and 2017) the severity of wetness was zero. For those years and seasons it means farmers would have to rely on another form of livelihoods since it was not possible to have adequate crops yields from the farms. Results of the incumbent study were in tandem to what farmers had experienced in which they said that for the past five years, it was only in the years 2013 and 2016 were there significant rains during the March- July growing season. From figure 5.4, the decade between 1997 and 2007 was the wettest with three pick periods perhaps mainly because of the El Nino effect that commenced in 1997. The previous period from around 1970 to 1996 was characterized by very few wet seasons, a situation that appears to be recurring since 2007. Evidently, from the year 2002 to 2017, the wet seasons have increased proportionately but are less severe. None of the wet seasons that have occurred during the last ten years attained a severity of wetness close to 1.0 compared to the previous decade. This result indicates a decline in rainfall amounts during March-July, the main growing season. Therefore, if farmers will still rely on rainfed agriculture then they ought to embrace the CSA interventions investigated in the current study for them to attain adequate sorghum yields to keep them food secure.

5.4. Rainfall Variability and Anomaly during the Short Rains [October-December] (Short Growing Season)

The October-December rains coincides with short growing season (SGS) that is mainly associated with cultivation of early maturing maize variety, beans, onions, pasture and fodder crops. Both the total and variability in are important aspects for the short rains because there are a number of crops that are grown during this season thus contributing to food security for many households. The season beginning October 1961 with an RAI value of 9.074 had the highest rainfall recorded. The other humid seasons occurred in the years: 1962, 1963, 1968, 1978, 1982, 1984, 1988, 1994, 1997 and 2007. From 2007, the trend indicated no humid situation observed during the short growing season (SGS) for the next ten years, supporting fears from farmers and key informants that the declining precipitation was aggravating food insecurity.

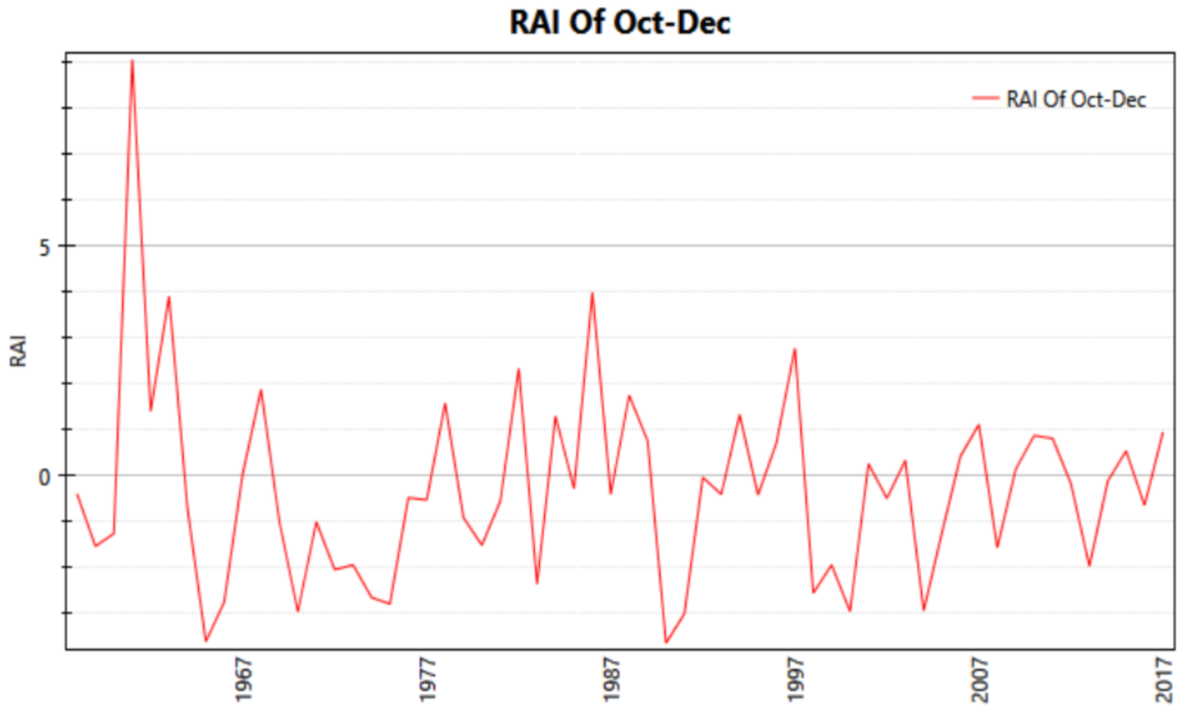

Figure 16: Rainfall Anomaly Index (RAI) of the October-December Short growing season (SGS)

Generally, the variability of rains during the short growing season is high with only the years, 1985, 1987, 1989 and 1992 receiving near normal rainfall. The other years, rains were mostly below average and erratic as indicated by the negative and positive RAI values. For instance between 1968 and 1978 there was not a single year that above normal rainfall was recorded, suggesting that maybe low yields were obtained in the stated period. Then between 1978 and 1988, five seasons were humid while the rest were dry. Important to note however is that, even though the seasons have remained erratic during the last ten years (2007 to 2017), the within season rainfall has considerably reduced as indicated by declining RAI values compared to the previous decade (1997 to 2007). Drought regimes were also considerably high and severe as shown in figure 18. From figure 16 eleven periods of drought were recorded. Three of which were extremely severe; 1965 (severity 2.65), 1990 (severity 2.67) and 1991 (severity 2.03). The dry period commencing October 1969 was the longest lasting 2556 days and severity of 7.552. The implication was probably there was no meaningful cultivation that took place for the five consecutive seasons, a trend that old farmers interviewed recounted during focus group discussion. However, the drought periods were fewer between 1977 and 1987, surprisingly so because it is during that period when the most severe drought was recorded, 1983-1984 (Figure 17)

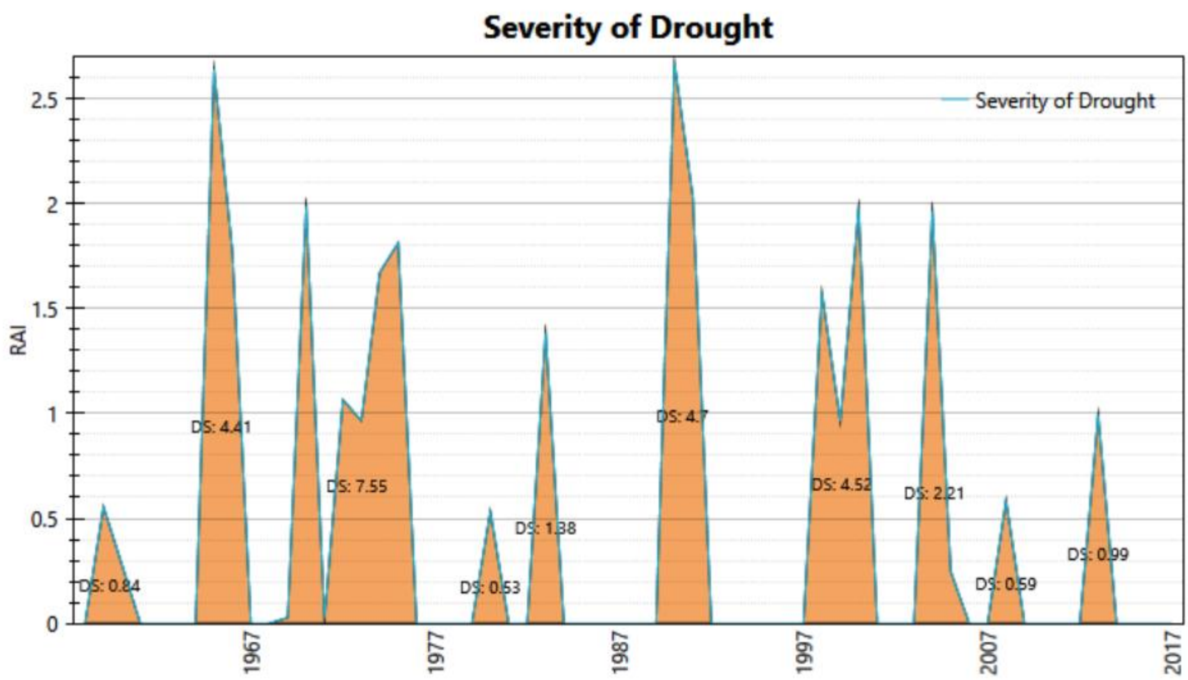

Figure 17: Rainfall Anomaly Index, Severity of Drought for the October-December Short Growing Season (SGS)

Table 14 shows the intensity and frequency of drought periods for the short rainfall season. This study further observed that even though there were no rains during the early part of the year, 1984, a substantial amount (356.2mm) fell during the October-December short growing season (SGS). From FGD findings, farmers did not take advantage of those rains mainly because they were caught unawares, highlighting the significance of greater cooperation between Meteorological Department (especially County Directors of Meteorology) and farmers' advisory services so that farmers are provided with weather forecasts promptly.

Table 13 : Rainfall Anomaly Index, Severity of Drought for October -December (Short Rainfall Season)

Number of drought	Start of drought period	Duration	Number of seasons	Severity of drought
1	1/1/1959	731	Two	0.838
2	1/1/1965	730	Two	4.40
3	1/1/1969	2556	Seven	7.552
4	1/1/1980	366	One	0.534
5	1/1/1983	365	One	1.384
6	1/1/1990	730	Two	4.698
7	1/1/1998	1096	Three	4.521
8	1/1/2004	731	Two	2.212
9	1/1/2008	366	One	0.587
10	1/1/2013	365	One	0.993

Another observation was a remarkable increase in drought periods between 1998 and 2007. A three season dry spell was recorded between 1998 and 2000. That duration was widely associated with the la Nina effect which followed the El Nino phenomena of 1997-1998. The findings show that contrary to perceptions by farmers that the El Niño effect covered the entire 1998 year this study shows the October – December short growing season of 1998, was characterized by a dry spell. The increase in the frequency of drought periods after the El Nino effect [as it's normally accepted that, there is always a drought following the El Nino] should remain a concern for policy makers in an attempt to address food security for the community. The drought pattern for the last ten years (2007-2017) [figure 17] shows the occurrence of the dry season after every five years. If the trend is to hold, then farmers should expect a dry season during the October-December 2018 growing season.

Results for the severity of wetness are almost the complete opposite of the drought periods. The wet periods were fewer than and not as severe as the drought periods as shown in Table 15 and Figure 18

Table 14 : Rainfall Anomaly Index, Severity of Wetness for the October -December Short Rainfall Season.

Number of wet period	Start of the wet period	Duration	Number of seasons	Severity of wetness
1	1/1/1961	1095	Three	11.409
2	1/1/1968	366	One	0.888
3	1/1/1978	365	One	0.581
4	1/1/1982	365	One	1.343
5	1/1/1984	366	One	0.302
6	1/1/1986	365	One	3.005
7	1/1/1988	366	One	0.759
8	1/1/1994	365	One	0.334
9	1/1/1997	365	One	1.781
10	1/1/2007	365	One	0.121

The wet period commencing October 1961 was the wettest with the severity of 11.409, a situation that extended up to the next two successive seasons in 1962 and 1963. From then onwards, the frequency of wet periods became low and wet periods shorter. For instance, between 1964 and 1977, only one low key wet season was recorded in 1968 (severity 0.888). A notable positive trend was observed between 1982 and 1988. During that interval, a substantial amount of rainfall was recorded in four of those years despite some of those seasons e.g. in 1984, falling in one of the driest years. The findings signify the importance of the October –December short rains in addressing food security.

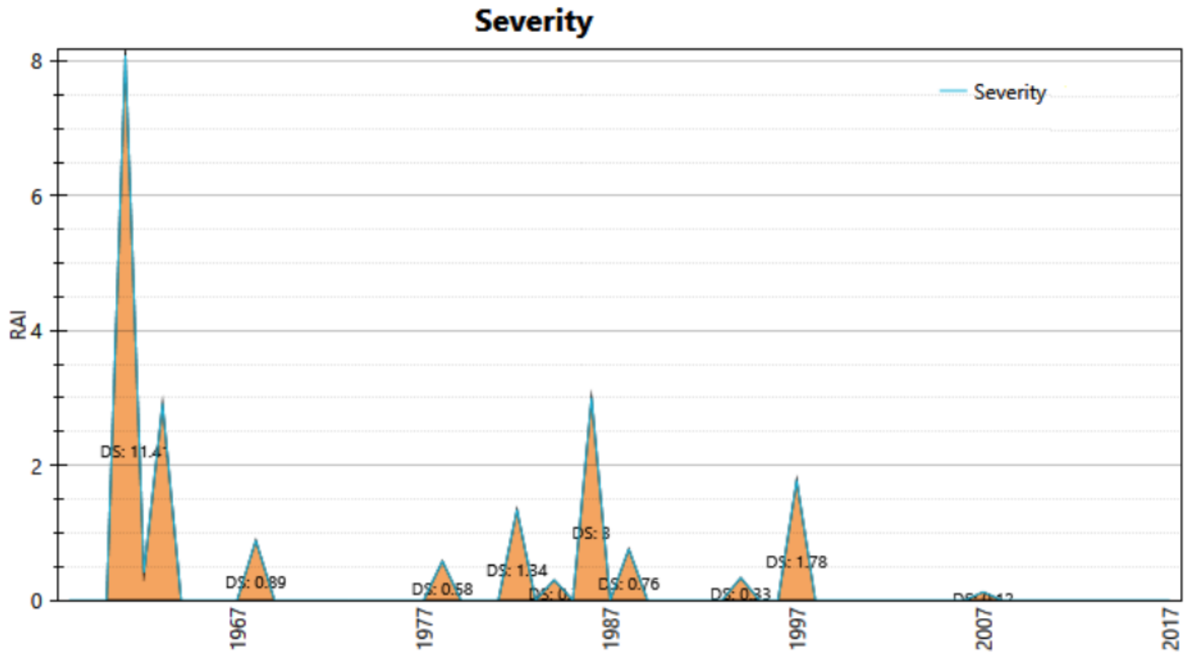

Figure 18: Rainfall Anomaly Index, Severity of Wetness for October -December short Rainfall Season

A wet season immediately followed a severe drought in 1984(Figure 19). Between 1997 and 2017, a period of twenty years, there was no significant wet season Apart from the year 2007 which recorded severity of wetness of a mere 0.1211, all the other years had a value of zero; meaning that, none of the October-December short growing seasons (SGS) attained adequate rainfall to support meaningful crop production.

5.5 Analysis of Historical Annual Rainfall Data Using Standardized Precipitation Index

In this study Standardized Precipitation Index as proposed by Mackee, et.al., (1993) was used to investigate the annual trend of droughts, the severity of drought and wetness during the study period. Analysis shows slightly over half the years there was no drought as indicated by positive yearly SPI values: 1958 (0.213), 1961(3.568), 1962(0.833), 1963(1.712), 1964(0.657), 1967(0.335), 1968(1.309), 1969(0.921), 1977(0.254), 1978(1.064), 1979(0.218), 1981(0.177), 1982(0.292), 1985(0.041), 1986(0.733), 1988(1.417), 1989(0.458), 1994(0.048), 1996(0.034), 1997(1.053), 1998(1.13), 2002(0.076), 2003(1.228), 2005(0.227), 2006(0.301), 2007(1.781), 2011(0.765), 2012(0.828), 2013(0.193), 2014(0.185) and 2016(0.598). However, these figures may be misleading as the absence of drought was not necessarily an indicator of favorable weather. A closer look will reveal, the majority of the years mentioned were only slightly wet as indicated by low SPI values of less than one (Figure 20).

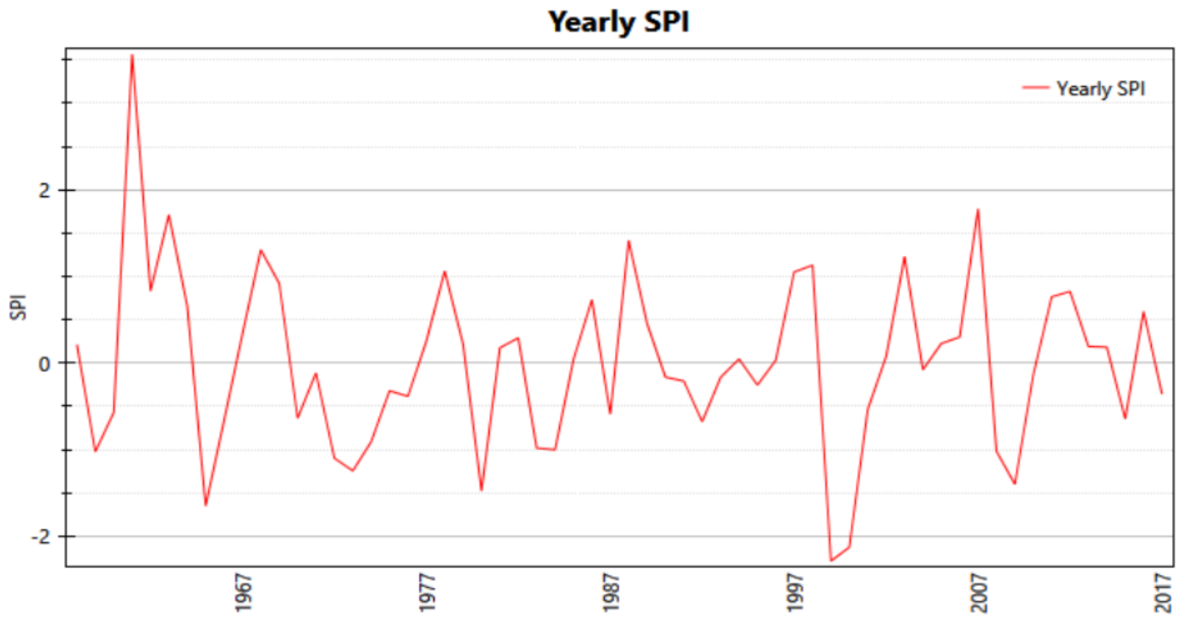

Figure 13: Yearly Standardized Precipitation Index (SPI) for the Historical precipitation 1958 to 2017

Only 1961 with an SPI Yearly index of 3.568 qualified to be an extremely wet year. Years: 1963(1.712), 1968(1.309), 1978(1.064), 1988(1.417), 1997(1.053) 1998(1.13) 2003(1.228) and 2007(1.781) with SPI values ranging from 1.5 to 1.99 could be described as very wet. Apart from a few discrepancies, it was evident beginning 1968 a wet year occurred every ten years. However as from the year 2007, not a single wet season has been observed, perhaps confirming that Climate Change to be a true phenomenon.

On the other hand, severe droughts were reported in 1999 (-2.285) and 2000 (-2.126). These results indicated that these years were driest and not the year 1984 as previously perceived by farmers. As noted earlier, in 1984 sufficient showers of rain were recorded during the October-December short growing season, negating the earlier assumption that the dry spell had spread over the whole year. Notably though, other drought years were observed occurring between periods that were wet. The first decade 1958-1967 was characterized by some years of very high rainfall but also within the wet years severe droughts also occurred. For instance after wet years of 1961 to 1964 the drought year 1965(-1.649) was witnessed. However none of the farmers interviewed could recall that. Again the drought was recorded in the years 1970(-0.635), 1971(-0.112), 1972(-1.097), 1973(-1.244), 1974(-0.907), 1975(-

0.32) and 1976(-0.383) signifying these to be the longest dry period. Beginning 1959-1960 seasons, there appears to be a recurrence of drought after every four to five years as follows: 1965, 1974-1975, 1980, 1984, 1987, 1990-1993, 1995, 1999-2000, 2004, 2008-2009 and 2015 (Table 16).

Table 15: Yearly Standardized Precipitation Index and Severity of Drought.

Drought number	Start of drought	Duration	Number of seasons	Severity of drought
1	1/1/1959	365	One	0.033
2	1/1/1965	365	One	0.659
3	1/1/1972	731	Two	0.361
4	1/1/1980	366	One	0.486
5	1/1/1984	366	One	0.01
6	1/1/1999	731	Two	2.431
7	1/1/2008	731	Two	0.435

This pattern shows that, although the frequency and intensity of drought is not as high as that of during 1967-1977 seasons, the absence of very wet years in recent times does not help to alleviate the drought situation. The fact remains, rains have diminished which makes the occurrence of a dry spell of any magnitude to be felt more unlike in the past.

The drought periods of 1980 and 1984 had a duration of one season each and severity of 0.486 and 0.01 respectively, which means 1984 wasn't the driest year as widely perceived. The reason for this was because the 1984 drought was indeed an aggravation of a long period of drought which had commenced in 1982 hence its high impacts. Figure 20 shows the intensity of the drought periods. Another observation was an increase in the duration of drought periods for the past twenty years. Droughts that have occurred since 1999 each have extended for two cropping seasons. The implications for that is drought situations are becoming the norm rather than the exception. The year 1999 marked the beginning of the longest and most severe drought (2.431) that lasted for two seasons. The situation recurred in 2008 for two seasons but the impacts were mildly felt because the drought was less severe (0.435) though cutting across the two cropping seasons. Another case for reference is the situation between 2015 and 2017. A mild drought was recorded in 2015 which was followed by a slightly wet period in the year 2016 and another dry season in 2017. From FGDs farmers reported having encountered drought for the three years consecutively. That confirmed that the little gains received during the wet 2016 year were not sufficient to erode the negative impacts of the mild drought experienced in 2015. Additionally, a mild drought of the year 2017 appears to have had huge impacts since the farmers reported no successful crop season for the last three years.

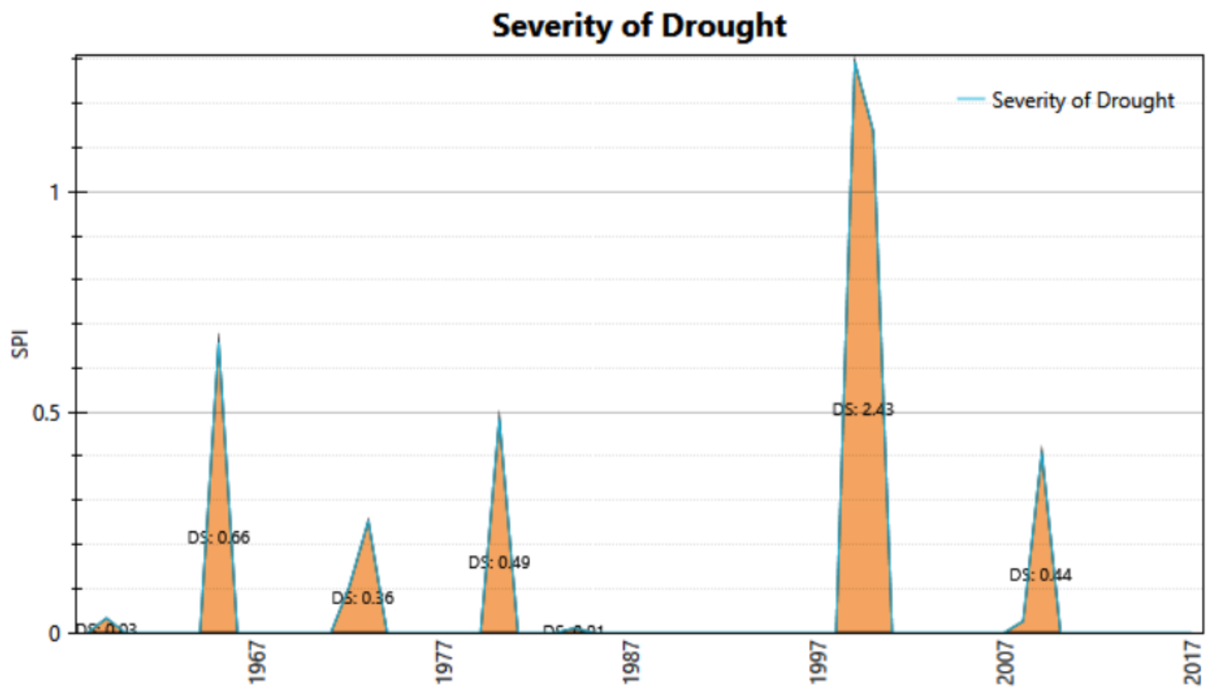

Figure 14: Yearly Standardized Precipitation Index, Severity of Drought Periods.

Results also indicated there were eight wet periods compared to seven drought periods. However the wet periods were shorter and less severe perhaps because of the geographic location of the study site falling under Arid and semi-Arid regions of Kenya. Apart from the wet period that commenced in 1997 which lasted for two seasons (731days), all the other wet periods lasted for only one season. The wet period was 1961 (severity of wetness 2.578). All the other periods were only mildly wet as indicated by the less than 1 for SPI value, the severity of wetness. A trend of recurring wet periods every 10 years as observed starting 1968, 1978, 1988, 1997 and 2007 with only one interruption of 2003. Notable though is the absence of a wet period since 2007 exacerbated by increasing frequency of drought. The findings of this study serve to demonstrate declining precipitation regimes, a situation that was corroborated by farmers in FGDs and by key informants. Table 17 shows the intensity and frequency of wet periods while figure 22 presents the same information graphically.

Table 16: Yearly Standardized Precipitation Index, Severity of Wetness

Number of period	Start of wet period	Duration	Number of seasons	Severity of wetness
1	1/1/1961	365	One	2.578
2	1/1/1963	365	One	0.722
3	1/1/1968	365	one	0.319
4	1/1/1978	365	One	0074
5	1/1/1988	366	One	0.427
6	1/1/1997	739	Two	0.208
7	1/1/2003	365	One	0.238
8	1/1/2007	365	One	0.791

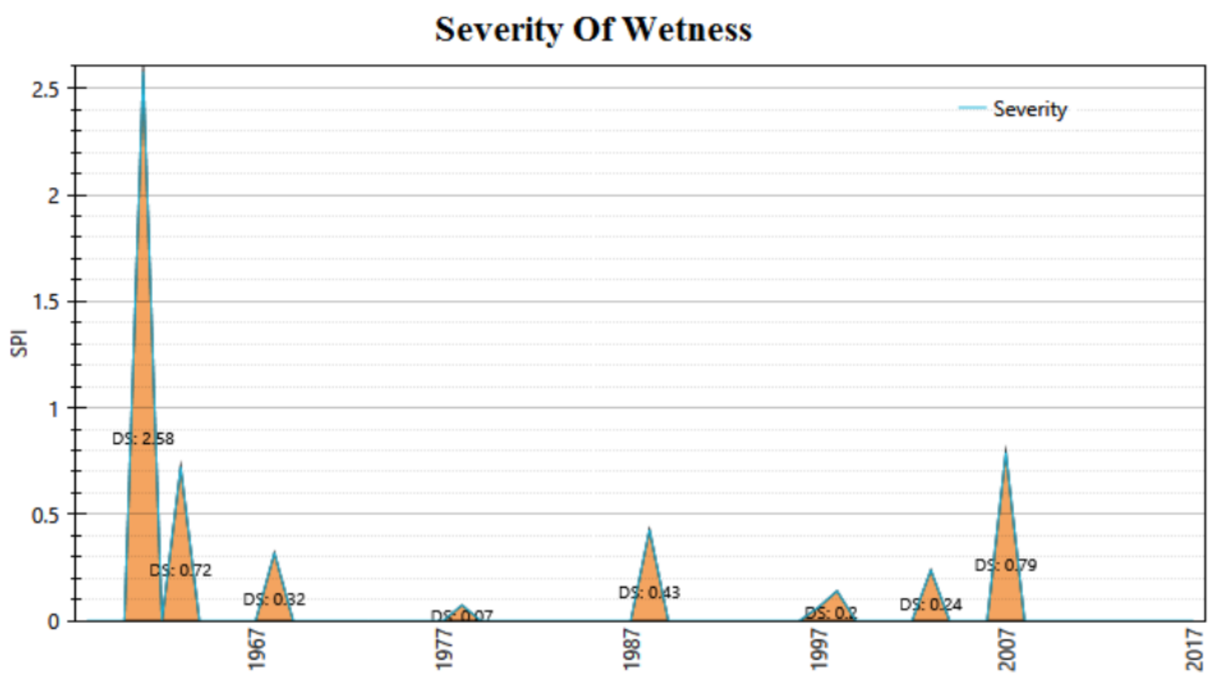

Figure 15: Yearly Standardized Precipitation Index and Degree of Wetness.

The findings from the current study places great importance to timely weather forecast supported by elaborate farmers advisory services so that farmers can maximize on the little rains. The absence of such collaboration was a core problem this study sought to address by harvesting rainwater in Zai pits and on parcels of land prepared by double digging as a medium to long term measures of addressing drought situation in the area. The findings from the incumbent study suggest that, where elaborate analysis of rainfall has been carried out then it may serve to inform development of suitable Climate-Smart Agriculture options for adaptation which are capable of being applied from the local context to global level.

CHAPTER SIX: AQUACROP MODEL, SIMULATIONS OF SORGHUM CROP YIELDS

6.0. Introduction.

In this section, the results and discussion are presented in the following parts; 1. Calibration and validation process; 2. Evaluation of simulated results. 3. Observed and simulated sorghum crop yields for current and future weather conditions under four IPCC emission scenarios; (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5). 4. Sorghum best cultivation practices based on Aquacrop scenario analysis for Climate-Smart Agriculture approach for Wiyumiririe.

6.1. Calibration and Validation Process.

This study used Aquacrop version 6.0 to: Calibrate; validate, simulate current and future Sorghum yields and prepare scenarios for policy makers based on the two adaptation options of double digging and use of Zai pits.

6.1.1. Climatic Parameters.

The model output for the monthly rainfall totals for the period (January 2016 to February 2019) is as shown in figure 22. Rainfall distribution indicated that there were two rainfall regimes, one beginning in March and the other one in October, evidence that was consistent with historical weather pattern and corroborated by farmers in focus group discussions.

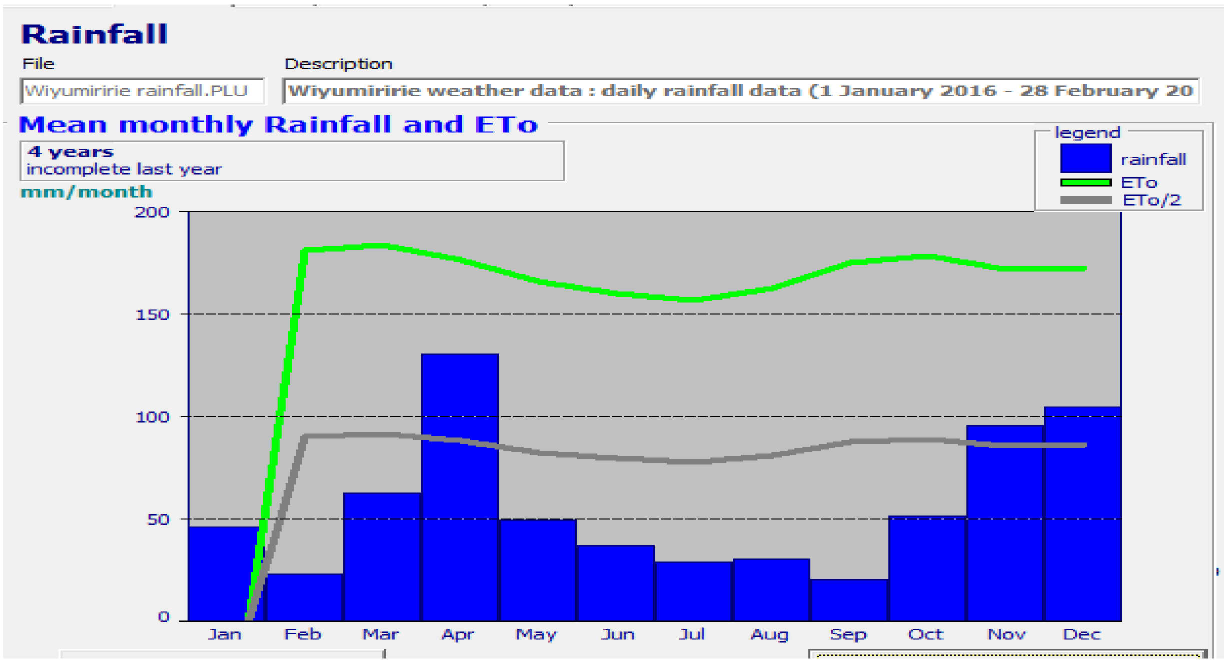

Figure 16 : Mean Monthly Rainfalls from January 2016 to February 2019

The onset of rains during the March 2016 season delayed substantially accounting for the late planting on April 5th, when a substantial amount of rainfall was received during the past 7 days. In the second season, rains came on time the reason for the early planting on October 6th 2016. During the third season, rains delayed so much to the extent that planting was done at the middle of the month (14th April, 2017), in a season where the least amount of rainfall was also received (192.8mm). In the same year, the coming of the short rains was less than accurate accounting for the late planting on 14th October 2017. However in the following year 2018, the long rains were timely hence the early planting on March 3rd 2018. In the same season the highest amount of rainfall was received (479.6mm). The amount of rainfall received per season is as shown in table 18

Table 17 : Rainfall received for every cropping season

Season	Amount of rainfall(mm)
April –September 2016	278.2
October 2016-February 2017	260.3
March 2017-September 2017	192.8
October 2017- February 2018	238.2
March 2018- September 2018	479.6
October 2018-February 2019	310.5

Seredo sorghum variety grows well in agro-ecological zones III and IV of Kenya with altitudes between 1150m and 1750m above sea level. The study area receives 250mm to 500mm of rainfall per season. During season three and four of the current study, the amount of rainfall received was less than the average requirements for the variety possibly accounting for the exceptionally low yield. From the current study rainfall amounts of between 260mm and 480mm per season is sufficient for proper growth and development of the Seredo variety of Sorghum. The study site was also higher in altitude meaning that it was cooler [minimum 5^0c] a situation that probably led to a longer growing season compared its average of 110-120days. In spite of that, the ability of the chosen CSA adaptation options to generate yields in a season where none was registered under conventional farming was evidence of the positive nature of the prioritized interventions. There was great variability on the onset of rains, [01/04/2016; 3/10/2016; 7/4/2017; 13/10/2017; 28/2/2018] a factor that contributed to the differences in the planting dates. That exacerbated by a lack of clear guidelines on the planting dates from the ministry of agriculture requires that in future farmers be better informed. Weather forecast, crop models and farmers advisory services were found to be a necessity but the absence of up to date weather data makes such efforts doubtful. To remediate some of the shortcomings encountered on the site, this study recommends that sowing be done when at least 20mm of rainfall has been received during the past seven days prior to planting.

In Kenya, Sorghum grows well within the temperature range of 15^{0}C and 35^{0}C. However in this study the base and upper temperatures (10^{0}C and 30^{0}C) were adopted for canopy development from the default values assigned in Aquacrop model. In some instances the temperatures exceeded the upper limit assigned by the model. Nevertheless, the absence of heat and cold stress symptoms as provided by Vollenweider and Günthardt-Goerg, (2005) confirmed the effects if any were minimal. In certain situations the minimum temperatures were below base temperatures, implying that the crops experienced cold stress more so in the months of January and July. Cold stress may cause male sterility, delayed maturity and reduction in yields. However apart from mild frost bite and delayed maturity this study was unable to quantify the full impacts of cold stress. The wide diurnal range in the months of January was also of concern and its impacts on canopy development may require investigation in the future. Figure 23 shows the model output for maximum and minimum temperatures during the study period

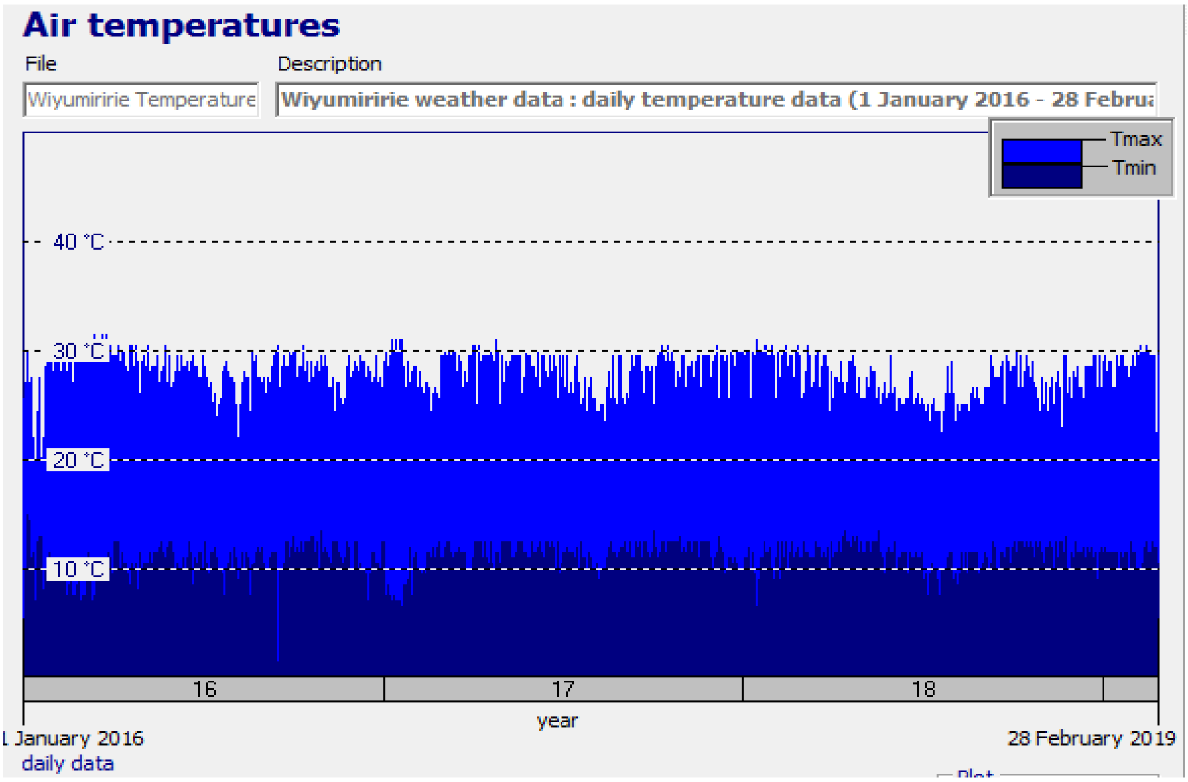

Figure 17: Daily Minimum and Maximum Air Temperatures from January 2016 to February 2019

6.1.2. Soil Parameters

Soil analytical data from the composite sample taken at the initial stage prior to cropping showed that the soils were moderately acidic for crop growth (pH 5.14) and contained the primary plant nutrients (NPK) other major nutrients and micronutrients, therefore regarded as fairly fertile for cultivation of Sorghum. Nevertheless, the soils had moderate levels of soil organic carbon and deficient in zinc. The recommendation from The Kenya Agricultural and Livestock Research Organization National Agricultural Research Laboratories (Kabete) was to apply at least 2tons/acre of farmyard manure or compost which was done as part of this study. Later analyzed soil samples from each treatment were used to derive one set of parameters for input files at the start of the growing cycle beginning March 2016. Table 19 shows the initial nutrient status of the soil.

Table 18: Nutrient Composition of Soil at the Start of the Trial

Fertility results	**Value**	**Class**
Soil pH	5.14	Adequate
Exch. Acidity me%	0.3	Adequate
Total Nitrogen %	0.24	Adequate
Total Org. Carbon %	2.61	Moderate
Phosphorus mg/kg	41	Adequate
Potassium me%	1.0	Adequate
Calcium me%	8.8	Adequate
Magnesium me%	2.40	Adequate
Manganese me%	1.36	Adequate
Copper ppm	1.00	Adequate
Iron ppm	29.8	Adequate
Zinc ppm	4.62	Low
Sodium me%	0.51	Adequate

Soil water content and fertility differed significantly from one treatment to the other due to the effect of double digging and construction of Zai pits, the study therefore opted to have a set of parameters for each treatment. In other words, each treatment was calibrated separately. Table 20 shows the soil profile characteristics at the beginning of the growing cycle that formed the input data to the model.

Table 19: Soil profile characteristics at the beginning of the cropping season

Treatment	TAW	PWP	FC	SAT	Ksat
DDFR	173	16.4	33.7	45.4	828
DD¾R	144	19.1	33.5	43.1	160.8
DD½R	147	18.5	33.2	42.5	1248
DD¼R	160	16.4	32.4	42.4	768
DDCONT	156	19.0	34.6	39.4	9.6
ZPFR	162	18.2	34.4	46.2	1752
ZP¾R	160	17.1	33.1	44.1	1562
ZP½R	172	18.2	35.4	44.0	3096
ZP½R	163	16.5	32.8	43.5	1872
ZPCONT	167	17.5	34.2	42.5	2.4
CONF	75	24.6	32.3	40.6	125

Initial soil conditions showed that the treatment for double digging and manure rates of 5tons/ha had the highest amount of total available water (TAW=173mm) while conventional farming had the least (TAW=75mm). Across board, it was evident that the prioritized interventions were effective in improving soil water content. It appears that the amount of water retained increased with increasing amounts of farmyard manure though the current study did not determine whether the differences were significant. Results of the calibration process showed acceptable goodness of fit between observed and simulated data for most of the treatments.

A notable difference was observed during the first cropping cycle for the intervention that involved Zai pits in which periodic water logging was observed yet the model had not predicted that. The problem was linked to the design of the Zai pits in which they retained more water than what the model simulated. Also, this study found the threshold for water saturation to be lower in Zai pits than what the model had predicted for the first growing season. To overcome that challenge, Zai pits were refilled to the ground level in subsequent cropping seasons although that appeared to have compromised their ability to retain more water as intended. However the reduction in biomass and yields was insignificant. In that respect, this study recommends that in situations where water logging is prevalent, Zai pits require to be redesigned or refilled to the surface. Information about Aquacrop and rainwater micro-catchment technologies was scanty; hence this study recommends more research into that area.

Generally interventions for double digging and Zai pit showed greater water retention compared to conventional farming. For instance in Zai pits where farmyard manure was added at 5tons/ha, the water level remained above the threshold for early canopy senescence during the entire cropping season, a situation that wasn't found under conventional farming. Figure 26 shows the model output for soil-water retention at the root zone for Zai pit treatment with incorporated farmyard manure at the rates of 5tons/ha.

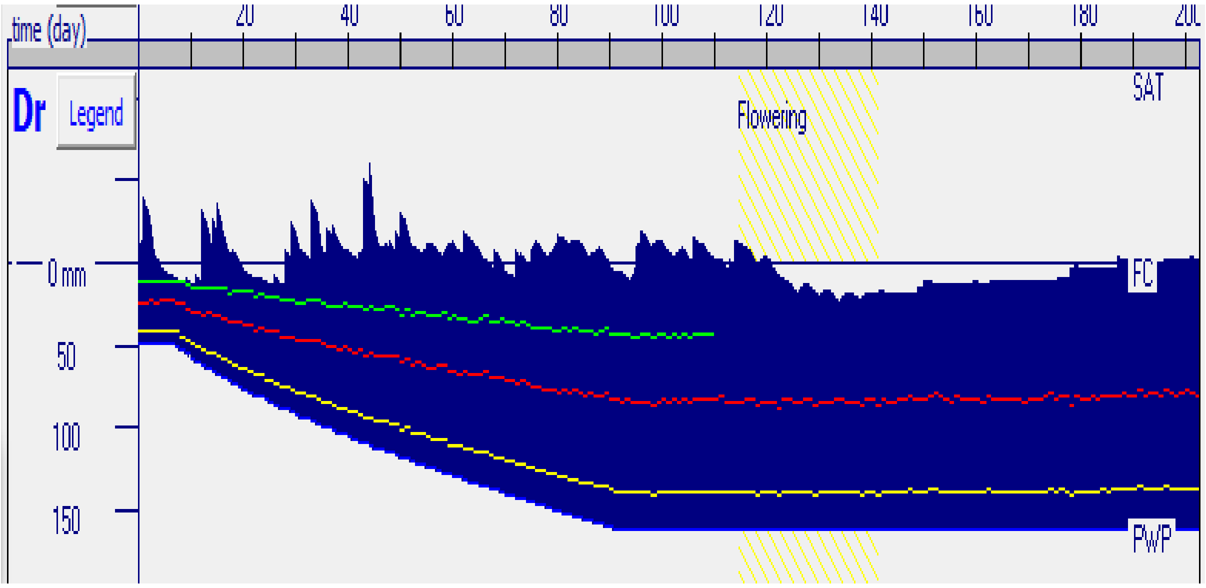

Figure 18: Soil Water Retention at the Root Zone during the Crop Cycle for Zai Pit Intervention, Validation Trial.

The figure shows water retention and movement in the root zone indicated by the blue color. The upper blue line (0mm) is the level at which water was at field capacity and the lowest point was a permanent wilting point (150mm).The green line indicates the threshold for canopy expansion; red, the threshold for stomata closure and yellow line, the threshold for canopy senescence. Since there's no time water level was below any of the three thresholds, it means the crops under this treatment did not experience any water stress. The sporadic moments when it was above field capacity indicates at times the plants had mild water stress due to flooding.

The findings from this study therefore indicate the intervention identified by farmers were effective as rainwater micro-catchment technologies as corroborated by the model output. The benefits were immediate in the form of reduction in water stress which translated into increased canopy development, biomass production and final yield. The strength with prioritized options was in their ability to harvest and rainwater water such that the crops cultivated didn't experience any water stress during the entire cropping season compared to the conventional farm. The findings therefore form a strong basis for up scaling. The effects of farmyard manure on soils have been studied widely and concur to this study in that it improves soil water holding capacity, soil structure and fertility, (Tedesco, et al., 2013; Jian-bing,et.al.,2014; Arumugam and Pontius, 2012 and Hanna, O. Ali. 1998).

6.1.3. Crop Parameters.

Non conservative crop parameters and management aspects were calibrated. Alongside that, soil fertility stress was considered. The crop parameters calibrated were those that relate to canopy cover, which was matched with field observations taking special attention to phenological stages. The plant spacing of 40cms by 30cms gave an approximate plant density of 83333plants/ha or 8.3plants/m^2 was critical in determining the initial canopy cover, percent and; time for reaching maximum canopy cover. Percent Canopy cover measured using Canopeo software installed in an Ipad provided field data for simulating canopy cover. Table 21 shows the crop parameters validated

Table 20: Aquacrop, Validated Data for Double Digging, Zai Pit and Conventional Farming

Parameter	Double digging	Zai pit	Conventional farming
Date of planting	2/3/2018	2/3/2018	2/3/2018
Plant density	83333plants/ha	83333plants/ha	83333plants/ha
Days to Maximum canopy cover	92	107	91
Maximum canopy cover	83%	80	70%
Duration of flowering	26	27	28
Days of building harvest	82	80	79
Senescence	162	164	134
Days to maximum rooting depth	92	93	94

Calibration for double digging and Zai pits interventions was feasible for all levels of farmyard manure, unfertilized control. However calibration for conventional farming where farmyard was incorporated at the rates of 3.75tons/ha or lower wasn't possible for inadequate canopy cover. Compared to the reference crop, the simulated effect of soil fertility stress for the treatments is provided in table 22. The effects were in form of reduction in maximum canopy cover compared to the reference crop, canopy growth coefficient, canopy cover per day and biomass water productivity. Biomass water productivity indicates how much biomass is produced relative to the amount of water lost via evapotranspiration.

Results indicated that where manure application rates were high (above 3.75tons/ha) soil fertility stress caused minimal reduction to maximum canopy cover (1 to 3 %), while the effects on biomass water productivity were substantial (15 to 41 %. The lower the amounts of farmyard manure applied the higher the soil fertility stress.

Plate 2: Sorghum crop in the field. The photograph shows the crop in the field during the 2018 long rainfall season about two weeks before reaching maximum canopy cover. The difference in treatments can be discerned from field observations in which crops on the left and lower side appear to be doing much better than those in the middle.

Table 21: Calibration for Soil Fertility

Treatment	Aboveground biomass	Maximum canopy cover	Canopy cover decline in season	Soil fertility stress	Effect (reduction)			
					CCx	CGC	CC%/day	WP*
DDFR	Near optimal	Close to reference	small	16	1%	1%	0%	32%
DD¾R	Near optimal	Slightly reduced	small	19	1%	3%	0.00	19%
DD½R	moderate	Slightly reduced	small	20	0	1%	0.01%	41%
DD¼R	About half	Slightly reduced	Medium	30	3%	2%	0.00%	51%
DDCONT	Poor	Strongly reduced	Strong	45	55%	33%	0.15%	40%
ZPFR	Near optimal	Close to reference	small	16	3%	1%	0.25%	15%
ZP¾R	Near optimal	Slightly reduced	small	19	6%	4%	0.01%	30%
ZP½R	moderate	Slightly reduced	small	20	10%	6%	0.02%	29%
ZP¼R	About half	Slightly reduced	Medium	30	20%	1%	0.02%	33%
ZPCONT	Poor	Strongly reduced	Strong	45	31%	7%	0.02%	54%
CONV	Very poor	Very strongly reduced	strong	45	49%	35%	0.25	63%

At half the recommended rates of farmyard manure the study observed the reduction on biomass production to be moderate, slight for maximum canopy cover and small for canopy cover. Even though the changes appeared minimal, the overall effects on canopy expansion, canopy growth coefficient and water productivity were huge accounting for the low final yields. In unfertilized controls (without manure applications), soil fertility stress was huge as indicated by the massive reduction in biomass produced, percent canopy cover and rate of canopy decline during the season. Compared to the reference crop, biomass production varied from poor to very poor, with a strong to very strong reduction in maximum canopy cover and average decline in canopy development during the season. The model quantitatively found the reduction to be substantial i.e. Maximum canopy cover was (55%), canopy growth coefficient (33%) and biomass water productivity (54%). The combined effect was a huge reduction in simulated biomass and yields which to a great extent corroborated with field observations.

That implied in addition to improving water holding capacity farmyard manure had the benefit of alleviating soil fertility stress, the reason for improved crop yields. Soil fertility was one of the problems identified by farmers. Due to high cost of inorganic fertilizers, the farmers had few options on how to address that problem. However the option of farmyard manure which they said was within reach may provide a plausible solution for improving soil fertility stress and improving soil water holding capacity. Given that calibration for soil fertility stress relied on qualitative analysis as proposed by Hsiao, et al., 2009; Raes, et .al., (2012), there may be need to carry out a more accurate calibration process based on actual in-season soil nutrient analysis.

6.1.4. Above Ground Biomass

The procedure of obtaining data for biomass is explained in the previous section. Calibration for biomass production was feasible apart from the treatments and seasons cited where adequate biomass production could not be attained. The measured biomass was from an average of four plants sampled for the exercise. Calibration was done effectively for all treatments where biomass produced wasn't a limiting factor without making any adjustments to normalized water productivity (1.70gms/m^2) and plant coefficients. Consequently most of the simulated biomass matched with field observations. The good simulation of biomass for production was partly due to the effective mechanism of collecting all the above ground biomass for analysis following the procedures found in Hanway and Weber (1971). Table 23 shows the validated field data for the long growing season.

Table 22: Field Data Used for Validation

Treatment	29 days		57 days		85 days		141days		169 days		Harvest
	CC	B	CC	B	CC	B	CC	B	CC	B	Biomass
DDFR	8.8	0.19	44.7	2.24	79.2	6.84	83.0	10.03	16.78	9.978	18.122
DD¾R	8.6	0.051	42.7	2.09	68.6	5.876	76.0	13.32	69.3	15.872	16.789
DD½R	8.4	0.048	30.2	2.011	62.4	4.524	75.0	9.317	66.6	11.872	13.157
DD¼R	6.4	0.043	30.6	1.094	60.3	3.924	72.8	8.342	68.6	9.864	11.569
DDCONT	2.2	0.040	11.9	0.946	26.2	2.124	28.8	4.293	24.6	5.614	5.672
ZPFR	7.6	0.05	21.4	1.346	68.3	4.981	79.4	12.123	70.2	14.634	15.982
ZP¾R	6.4	0.049	18.3	1.297	65.7	4.901	74.8	9.916	68.5	12.972	14.986
ZP½R	5.6	0.043	20.1	1.341	66.4	4.607	72.0	10.761	59.7	12.106	13.056
ZP¼R	5.5	0.041	18.1	1.249	54.7	3.563	61.8	8.916	57.3	10.275	11.284
ZPCONV	2.1	0.031	12,6	0.958	19.4	1.994	25.0	4.528	12.7	4.913	4.994
CONV	.1	0.012	3.4	0.886	9.8	1.243	7.9	1.472	2.2	1.520	1.641

On average in all treatments seedlings attained an initial canopy cover of 0.42% but attained maximum canopy cover, onset for flowering and senescence at different times. The first measurements were carried out on the 29th day after sowing and after weeding to avoid wrong estimations of canopy cover since the Canopeo software uses green coloration on the field to calculate percent canopy cover. Results indicate that during the first month, the crops cultivated under double digging had a head start as shown by the relatively higher values for canopy cover which translated to more biomass. That could partly be explained by the ability of soils to retain more water as shown by the higher values for TAW (Total Available Water). In subsequent stages, the trend was almost similar such that by the end the intervention for double digging recorded the highest crop yields. Under conventional farming both canopy development and biomass production was low mainly due to water and fertility stress such that in some instances the crops had inadequate canopy cover for effective calibration. Still in others, due to water stress, even with substantial canopy development yields produced were low. Generally biomass production was low during the first 57 days after planting and only managed to pick around 85 days of planting. The factors that might have contributed to slow accumulation of biomass at early stages may be linked to the slow pace of decomposition of farmyard manure to release nutrients. The other reason was the high altitude and lower temperatures at the study site compared to the areas where Seredo variety of Sorghum is often cultivated.

Sorghum is generally a short day plant, meaning that it would mature faster where nights are longer than days. However under tropical semi-arid regions where it was cultivated, the length of days and nights are almost equal. Consequently the neutral day conditions, higher altitude and low temperatures may account for the longer duration it took for the variety to mature during the long rains growing season.

6.1.5. Comparison of observed and simulated Sorghum crop yields for Current weather conditions.

The observed and simulated yields are as shown in table 24. Calibration for yields entailed determining the Harvest Index (HI) by dividing the yields by biomass at harvesting. Results indicated that for higher yields the Harvest Index (HI) approached 50% while for lower yields the values were very low. For most treatments the observed yields were higher than simulated ones though the difference was insignificant. Part of the variation could be due to experimental errors and calibration process which for most parameters was through trial and error as described by the developers of Aquacrop (Hsiao, et al., 2009; Raes, et .al., 2012). That notwithstanding, the high agreement for the goodness of fit between observed and simulated results for most treatments was encouraging.

Table 23: Actual Productions From Field Data and Simulated Using Observed Weather Data.

Treatment	Production based on actual field observations		Simulated production based on observed weather data		
	biomass t/ha	Yields t/ha	Potential biomass t/ha	Actual biomass t/ha	yield t/ha
DDFR	18.122	9.126	21.040	17.677	8.839
DD¾R	16.789	8.2945	20.570	16.648	8.344
DD½R	13.157	6.582	18.550	13.033	6.446
DD¼R	11.874	5.896	18.550	11.312	5.589
DDCONT	5.672	2.792	12.785	5.166	2.093
ZPFR	15.982	8.342	18.739	15.914	7.957
ZP¾R	14.986	7.491	18.448	14.945	7.473
ZP½R	13.056	6.448	18.753	12.992	6.309
ZP¼R	11.284	5.438	18.378	10.813	5.209
ZPCONT	4.994	2.316	12.046	4.283	1.834
CONFARM	1.864	0.632	14.728	1.972	0.036

The highest observed yields (9.126t/ha) were obtained from the double digging treatment and farmyard manure applied at the rates of 5tonns/ha. Those yields were 9.978% above that of Zai pit of similar treatment. Compared to simulated results the yields were higher by 3.145%. The lowest yields recorded were from conventional farming with farmyard manure applied at 5tons/ha. No yields were obtained for conventional farming at lower quantities of farmyard manure due to the limited canopy and biomass production. Simulated results showed a huge gap between potential biomass verses actual biomass. The high potential for the chosen CSA adaptation options means there is room for improvement by addressing soil fertility stress among other factors. Non limiting soil fertility conditions were not investigated in the current study probably to avoid scorching effects that are often associated with high quantities of farmyard manure applications.

The trend in the yields could partly be explained based on the effectiveness of the prioritized micro-catchment technologies for harvesting rainwater and the quantities of farmyard manure. Crops under all treatments experienced temperature stress of 12% so the differences in crop yields could only be accounted for by the variation in the two adaptation technologies and the amount of farmyard manure incorporated which appear to have altered soil physical properties and fertility differently. At the beginning of the cropping cycle, treatments where manure application rates were 3.75tons/ha or more, the initial soil water content was high giving those crops a head-start as indicated by the higher values for canopy cover and biomass produced. Still the water levels remained high during most important phenological stages such that crops did not exhibit any water stress that could have caused significant reduction in canopy expansion, stomata closure or trigger early senescence. However at lower rates of farmyard manure, various forms of water stress were recorded (Table 25).

Thirty days after planting, results showed that the water level had fallen slightly below field capacity for double digging and Zai pits treatments but the crop only experienced 1% reduction in canopy development which was insignificant. There was neither stomata closure nor early senescence. At the same time, crops had already formed 0.19tons/ha Zai pit (0.05 tons/ha of biomass respectively. On the other hand crops cultivated under conventional farming had at that time only formed 0.012tons/ha of biomass which was nearly 76% less primarily because of water stress that caused 54% reduction in canopy expansion and 3%. closure of stomata.

Table 24 : Effects of Water Stress on Crop Development

Treatment	Water stress		
	Canopy expansion	Stomata closure	Early senescence
DDFR	0	0	0
DD¾R	0	0	0
DD½R	2	15	0
DD¼R	18	18	0
DDCONT	27	28	0
ZPFR	0	0	0
ZP¾R	0	0	0
ZP½R	3	15	0
ZP¼R	22	18	0
ZPCONT	29	31	0
CONFARM	55	48	0

At half rates of manure applications crops under Zai pits experienced water stress that caused 2%, 3% reduction in canopy expansion and 15% stomatal closure respectively. At quarter rates water stress caused 18% reduction in canopy expansion for double digging and 22% for Zai pits. For the unfertilized control, water stress was moderate thus not sufficient to trigger early senescence.

For the crop growing under conventional farming, the stress conditions experienced during the early days of crop development prevailed and 113 days severe stress was evident in form of reduced canopy expansion and stomatal closure. There was full stress whereby canopy expansion stopped altogether. There was the closure of stomata that triggered early senescence of (5%). By the end of the growing season water stress was severe accounting for 55% reduction in canopy cover, 48% stomatal closure triggering early senescence. Moreover there was limited pollination, which implied meager fertilization hence minimal grain formation. Eventually, the crop could not attain maximum values for Harvest Index (HI) due to limited canopy cover, a phenomenon that was matched with field observations. Overall and based on the amount of water stress recorded, it was easy to deduce that the intervention for double digging was better in terms of water holding capacity followed by Zai pit and conventional farming last.

6.2. Evaluation of Simulated Results

Evaluation of simulated verses observed data for canopy cover, biomass production and soil water content was carried out using five inbuilt statistical indexes as discussed in chapter 3.
The Pearson correlation coefficient generates values of between +1 to -1 since all values obtained were positive and within the range of +1 to -1, first it means there is consistency in the observed data relative the simulated ones. For all treatments the values were above 0.7, implying that whenever there was an increase in the observed readings there was a corresponding increase in the simulated results. For instance, for biomass production six treatments, (DDFR, DD¾R, ZAIF¾R, ZP¾R, ZP½R, ZP¼R and ZPCONT), out of 11 attained a near perfect match between observed and simulated yields. Two other treatments for canopy cover development (DDCONT AND ZPFR) and one for soil water content (DD¼R) attained the same. By that it means the association between observed and simulated results was highest for biomass production, followed by canopy cover finally soil water content.

The Root Mean Square (RMSE) measures of how far observed data departs from a regression line. Put differently, RMSE informs how observed data points are concentrated relative to models predicted values or how accurately model predicts the response. The smaller the values, the closer the concentration to the regression line. Based on that, the observed biomass data was closer to the predicted values compared to that of and soil water content and canopy cover with average RMSE values of 0.47(biomass), 10.77(Soil water content) and 4.04 (canopy cover) respectively. Therefore, the Aquacrop was more accurate in predicting values for biomass production than for the other parameters evaluated. Within the treatments, observed data for biomass was closest to the simulated in the order of ZP½R (RMSE=0.2), DDFR (RMSE=0.3), DD¾R (RMSE=0.3), DDCONT (RMSE=0.3), ZP¼R (RMSE =0.5), ZPFR (RMSE=0.5), ZP¾R (RMSE=0.6), ZPCONT (RME=0.6) and DD½R (RMSE=0.9). For canopy cover the order was follows DDCONT (RMSE=1.3), ZPCONT (RMSE=3.0), ZP¼R (RMSE=3.2), ZP¾R (RMSE=3.4), ZPFR (RMSE=3.6), DD¼R (RMSE=4.2), DD¾R (RMSE=5.1), DD½R (RMSE=5.3), ZP½R (RMSE=6.4) and DDFR (RMSE=4.9). Likewise, the order for soil water content was; ZPCONT (RMSE=7.7), DD½R (RMSE=8.1), ZPFR (RMSE=8.4), ZP¾R (RMSE=8.5), DD¼R (RMSE=10.3), DDCONT (RMSE=10.6), DD¾R (RMSE=10.7), ZP½R (RMSE=11.1), DDFR (RMSE=13.6) and ZP¼R (RMSE=18.7).

Table 25 : Results for Evaluation of Simulated Data

Treatment	Statistical index	Canopy cover	Biomass	Soil water content
DDFR	r	0.99	1.00	0.96
	RMSE	4.9	0.3	13.6
	CV(RMSE)	10.2	3.1	8.4
	EF	0.98	1.00	0.87
	d	0.99	1.00	0.96
	Average OB	48.4%	10.887t/ha	162.9mm
	Average SM	48.9%	10.635t/ha	158.3mm
DD¾R	r	0.99	1.0	0.97
	RMSE	5.1	0.3	10.7
	CV(RMSE)	11.5	3.5	7.5
	EF	0.97	1.00	0.93
	d	0.99	1.00	0.98
	Average OB	44.1%	9.942t/ha	143.6mm
	Average SM	43.4%	10.085t/ha	144.8mm
DD½R	r	0.99	0.99	0.98
	RMSE	5.3	0.6	8.1
	CV(RMSE)	13.1	8.2	6.2
	EF	0.97	0.98	0.96
	d	0.99	1.0	0.99

	Average OB	40.6%	7.831t/ha	131.2mm
	Average SM	41.5%	8.037t/ha	131.7mm
DD¼R	r	0.99	0.98	1.00
	RMSE	4.2	0.90	10.3
	CV(RMSE)	10.5	13.9	8.3
	EF	0.98	0.95	0.94
	d	1.00	0.99	0.98
	Average OB	39.5%	6.623t/ha	123.3mm
	Average SM	40.2%	7.147t/ha	131.9mm
DDCONT	r	1.00	0.99	0.98
	RMSE	1.3	0.30	13.1
	CV(RMSE)	8.4	9.3	10.6
	EF	0.99	0.97	0.91
	d	1.00	0.99	0.97
	Average OB	15.5%	3.416t/ha	123.2mm
	Average SM	14.4%	3.334t/ha	129.8mm
ZPFR	r	1.00	1.00	0.96
	RMSE	3.6	0.5	8.4
	CV(RMSE)	8.3	5.1	4.2
	EF	0.99	0.99	0.65
	d	1.00	1.00	0.88
	Average OB	43.1	9.176t/ha	201.5mm
	Average SM	40.5	8.873t/ha	195.1mm
ZP¾R	r	0.99	1.00	0.91
	RMSE	3.4	0.6	8.5
	CV(RMSE)	8.4	7.1	4.5
	EF	0.99	0.99	0.66
	d	1.00	1.00	0.88
	Average OB	41.1%	8.426t/ha	189.2mm
	Average SM	40.1%	8.225t/ha	184.5mm
ZP½R	r	0.98	1.00	0.98
	RMSE	6.4	0.2	11.1
	CV(RMSE)	15.9	2.6	7.9
	EF	0.96	1.00	0.93
	d	0.99	1.00	0.98
	Average OB	40.0%	7.974t/ha	140.3mm
	Average SM	37.7%	7.890t/ha	134.7mm
ZP¼R	r	0.99	1.00	0.95
	RMSE	3.2	0.3	18.7
	CV(RMSE)	9.5	5.0	14.0
	EF	0.99	0.99	0.85
	d	1.00	1.00	0.96
	Average OB	33.4%	6.774t/ha	133.0mm
	Average SM	32.4%	6.591t/ha	122.9mm
ZPCONT	r	0.95	1.00	0.99
	RMSE	3.0	0.6	7.7
	CV(RMSE)	24.1	17.1	6.4
	EF	0.90	0.91	0.96
	d	0.97	0.97	0.99

	Average OB	12.4%	3.280t/ha	113.1mm
	Average SM	11.8%	2.825t/ha	110.8mm
CONVFR	r	0.99	0.97	0.93
	RMSE	1.4	0.2	22.6
	CV(RMSE)	17.4	14.7	15.9
	EF	0.97	0.92	0.41
	d	0.99	0.98	0.85
	Average OB	8.1%	1.338t/ha	142.5mm
	Average SM	7.6%	1.322t/ha	162.1mm

6.3. Impact of Future Climate on Sorghum Growth and Development Based on IPCC Emission scenarios

Under the reference IPCC emission scenario RCP 6.0, the impacts of future climatic conditions to Sorghum growth, development and final yields vary across treatments. In the medium term (2038) crop under most treatments will experience temperature stress of 28% which will be expected to drop to 24% by the year 2068. Crops cultivated under double digging plus 5tons/ha of farmyard will by the year 2038 undergo water stress that may cause a 3% reduction in canopy development and 1% closure of stomata respectively. For the same treatments, the crops may by 2068 experience 24% temperature and water stress that may cause a reduction in canopy expansion by 3% and stomata closure of 1% respectively. The combined simulated effects by Aquacrop are a yields increase of 30.65 % above the current rates.

Crops cultivated under double digging and half rates of manure will by 2038 experience temperature stress of 28% and water stress that may lead to a 43% reduction in canopy expansion and 19% closure of stomatal. By 2068 the stresses will cause a 50% reduction in canopy expansion and 22% closure of stomata. Aquacrop simulates a combined effect showing an increase in yields by 6.46% for the year 2038 and 23.21% by the year 2068. Intervention for double digging without any manure applications indicates that crop will experience temperature stress of 27% (2038) which will drop to 22% by 2068. On the other hand, water stress may cause 54% reduction in canopy expansion and 31% stomata closure for the year 2038 which Aquacrop indicates will lead to an increase in yields by 3.86% above the current rates. By the year 2068, Aquacrop projects water stress will have effect inform of 57% reduction in canopy expansion and 28% closure of stomata. The combined effect pointing to an increase in yields by 8.64% above the current rates

Crops cultivated under Zai-pits and manure rates of 5tons/ha crops will experience temperature stress of 29% and water stress that may cause 1%reduction in canopy expansion but no effect on stomata closure. The combined effect will be an increase in yields by 10.39% above the current rates in the year 2038. By 2068 crops will suffer 24% temperature stress. Water stress may cause 1% reduction in canopy expansion and 0% closure of stomata respectively. The combined effect will be an increase in yields by 28.83% above the current rates. At half rates of farmyard manure by 2068 crops will experience temperature stress of 31% and water stress that will cause 36% reduction in canopy expansion and 20% stomatal closure. The combined effects will be an increase in yields by 5.083% above the current rates. Without any manure applications crops under Zai pits will experience 21% temperature stress by 2068 and water stress that will cause 61% reduction in canopy expansion and 23% closure of stomata. The combined effect simulated by Aquacrop will be an increase in yields by 21.33% above the current rates.

The findings from this study show that under future climatic scenarios increments in Sorghum yields will be observed both in the medium and long term which concur with similar studies (Chianti, et. al., 2003; Turner and Rae, 2013; Sultan, et al., 2013; Chijioke and Haile 2011; Gwimbi et al., 2013) However these results may be misleading because the study has also shown increase in temperature stress from currently at 6% to as high as 31% by 2068 for some treatments. The compounding effects of water stress estimated to cause 61% reduction in canopy expansion and 31 % stomata. Moreover the impacts of altered weather patterns to crop physiology, soil chemical properties, crop pests and diseases, necessitates we take any increment in yields with caution. Table 27 shows the yield projections based on the four IPCC scenarios

Table 26 : Sorghum Crop Yields for Current and Under Future IPCC RCP Scenarios

Treatment	RCP	2018	2028	2038	2048	2058	2068
DDFR	2.6	6.781	7.143	7.438	7.661	7.816	7.928
	4.5	6.768	7.166	7.616	8.043	8.415	8.702
	6.0	6.743	7.108	7.512	7.962	8.400	8.810
	8.5	6.805	7.298	7.848	8.381	9.013	9.725
DD¾R	2.6	6.474	6.527	6.782	6.962	7.166	7.222
	4.5	6.463	6.547	6.944	7.307	7.676	7.904
	6.0	6.439	6.496	6.851	7.235	7.662	7.991
	8.5	6.497	6.664	7.152	7.610	8.199	8.774
DD½R	2.6	4.797	4.939	5.026	5.153	5.231	5.296
	4.5	4.788	4.956	5.150	5.389	5.608	5.805
	6.0	4.770	4.915	5.078	5.356	5.598	5.877
	8.5	4.815	5.050	5.311	5.625	5.988	6.435
DD¼R	2.6	4.052	4.180	4.260	3.963	4.348	4.473
	4.5	4.045	4.194	4.366	4.167	4.697	4.921
	6.0	4.029	4.159	4.305	4.122	4.688	4.984
	8.5	4.068	4.274	4.506	4.715	5.020	5.477
DDCONT	2.6	1.305	1.331	1.329	1.283	1.254	1.208
	4.5	1.302	1.336	1.368	1.362	1.371	1.383
	6.0	1.296	1.323	1.346	1.345	1.368	1.408
	8.5	1.300	1.362	1.419	1.438	1.500	1.601
ZPFR	2.6	6.061	6.348	6.588	6.740	6.918	7.021
	4.5	6.050	6.368	6.746	7.076	7.431	7.674
	6.0	6.028	6.317	6.654	7.007	7.418	7.766
	8.5	6.083	6.484	6.946	7.370	7.931	8.528
ZP¾R	2.6	4.688	4.815	4.989	4.650	5.031	4.860
	4.5	4.679	4.870	5.115	4.899	5.445	4.823
	6.0	4.662	4.831	5.042	4.845	5.434	4.899
	8.5	4.705	4.959	5.298	5.713	5.713	6.044
ZP¼R	2.6	3.748	3.854	3.904	3.777	3.708	3.459
	4.5	3.741	3.866	4.003	3.988	4.021	3.829
	6.0	3.728	3.835	3.946	3.944	4.013	3.884

ZPCONT	2.6	1.057	1.087	1.048	1.039	1.076	1.091
	4.5	1.055	1.091	1.077	1.103	1.177	1.252
	6.0	1.050	1.080	1.060	1.089	1.174	1.274
	8.5	1.061	1.114	1.117	1.164	1.320	1.453
CONVFARM	2.6	0.00	0.00	0.00	0.00	0.00	0.00
	4.5	0.00	0.00	0.00	0.00	0.00	0.00
	6.0	0.00	0.00	0.00	0.00	0.00	0.00
	8.5	0.00	0.00	0.00	0.00	0.00	0.00

6.4. Scenarios for Policy Makers.

This study investigated how Aquacrop model can help developing scenarios for policy makers. Basically the scenarios considered were for the two adaptation options of double digging and making of Zai pits in which varying levels of farmyard manure was incorporated and Seredo variety of sorghum cultivated.

Under the current weather conditions and near optimal levels of soil fertility the production of Seredo cultivated in the parcels of land prepared by double digging currently stands at 9.126tons/ha which is more than double the average production in Kenya of 4tons/ha and has the potential to go up to 10.86tons/ha under unlimiting conditions of soil fertility. Since no water stress was observed in that treatment, the focus may have to shift to soil fertility in order to cross the yield gap. In the event farmers may not have adequate farmyard manure and thus only managed to apply half the recommended rates the output from the long season will be 6.852tons/ha, not bad at all because they are above the normal rates for the region. In that respect, famers can be advised to make a choice between investing more in farmyard manure or take the risk of having lower yields.

Currently the production of the Seredo variety cultivated under Zai pits and 5tonss/ha is 8.342tons/ha which is 8.59% lower than that of double digging of equal amounts of farmyard manure. From field trials it was observed that the labor requirements were almost similar for the two adaptation options. Thus, all other factors being equal, farmers can be advised to adopt double digging. Projecting into future, both interventions will continue to register higher sorghum yields compared to the conventional farming. The huge advantage of the two interventions in water retention and mitigation against water stress is a strong point that cannot be wished away. The importance of farmyard manure is captured in evaluating the yield from the unfertilized controls, i.e. without any manure applications. For the double digging the current yields were 2.792tons/ha and Zai pits 2.316tons/ha which were respectively lower by 52.65% and 57.41% than treatments where farmyard manure was applied at only a quarter of the recommended rates. This means that it would not make a lot of sense to invest a lot of labor in double digging and making Zai pits and fail to apply farmyard manure. Consequently, the farmers require advice to apply farmyard manure as a standard practice. Aquacrop helped in identifying the yield gaps, extrapolated from potential verses actual biomass produced. Taking the Harvest Index (HI) to be 50% it was evident that it's possible to attain higher yields by remediating soil fertility and water stress for treatments with low applications rates of farmyard manure. With future weather conditions pointing to increased water and temperature stress and no foreseeable infrastructure for irrigation, efforts may be required to put the interventions investigated in this study into Climate-smart Agriculture policy for the area. The initial labour requirements might be high, but in the long run the interventions are worth because of increased crop production and the associated positive impact in alleviating food security for the residents.

CHAPTER SEVEN: SYNTHESIS AND EVALUATION

7.1. Discussion

Over time humanity has been faced by a myriad of challenges in trying to overcome food insecurity. With industrialization came mechanized farming, irrigated agriculture and use of inorganic fertilizers which for a moment appeared to solve the problems of chronic global food insecurity. However these claims of success were overshadowed by the negative effects brought by the same innovations. For instance, excess use of fertilizers rendered soils sterile; huge dams for irrigation displaced thousands of people, biotechnology brought controversies because of genetically modified foods while; burning of fossil fuel is currently endangering the earth's protective layers besides causing Climate Change whose associated water and temperature stress have impacted negatively on crop yields.

At the same time increasing human population in Sub Sahara Africa that hasn't been matched by economic growth, coupled with reduction in farming sizes has undermined the ability of the farmers to engage in meaningful farming. Therefore each claim of success by humans has brought new challenges in a paradox of a cure being worse than the disease. This implies that unless current solutions are reevaluated and redesigned they are likely to cause serious problems for generations to come. Part of the problem of past generations has been the mode and pattern of research in which greater emphasis has been placed on disciplinary specialization with little or no knowledge sharing across boundaries (Valerie et al., 2010). In the end due to compartmentalization of knowledge and occasional disciplinary competition, humanity has ended up with a plethora of environmental problems, top on the list being Climate Change (Valerie et al., 2010).

Fortunately, other mode of knowledge production exist which if put into practice may attain sustainability. According to Rittel and Webber, (1973) such problems like Climate Change are diabolical in that solutions tend to generate more problems in a cyclical manner without clear solution at the end. Given that such problems originate from the society that creates them in the first place, it's imperative to involve community members in new avenues for knowledge production. Additionally, new policy structures as well as new approaches to research need to be considered. Instead of following the conventional disciplinary approach, the emerging challenges like those brought by Climate change necessitates both the inquirer and the decision maker to explore all plausible ways of knowledge production in a truly recursive manner.

At the study site as mentioned in previous chapters the target community was experiencing chronic food shortage, a situation that was becoming worse with time. The agricultural production system was highly sensitive to environmental hazards and the low adaptive capacity of the residents made the situation worse

So for the current study to help them overcome food insecurity and build resilience to climate change, a paradigm shift from the conventional disciplinary approaches was necessary. In other words, rather than limit to only one method of inquiry a holistic approach that embraced all forms knowledge production was paramount to match with the emerging threats of climate change which were undermining their food security. This study was such an effort in adopting the transdisciplinary approach in trying out Climate-Smart Agriculture options in an attempt to solve the chronic food shortage and build resilience to Climate Change for the smallholders of Wiyumiririe Laikipia County. Besides climate change, endemic poverty, illiteracy and archaic farming methods were adversely mentioned in FGD as drivers for food insecurity.

The choice of this approach was due to the complexity of the problem that required pluralism in knowledge production and wider inclusivity of stakeholders. In this context transdisciplinary was taken to be the collective understanding of the issue at hand by including the personal, local, strategic and specialized forms of knowledge into a workable package. It is different from multidisciplinary (a combination of disciplines) and interdisciplinary (an integration of disciplines) researches which were found inadequate. Transdisciplinarity is an approach that envisages teamwork and collaborative learning process through its three main stages; problem identification, co- creation of knowledge and reintegration of the task of carrying out stakeholder analysis to help in identifying all those affected by the problem directly or indirectly, their respective roles in addressing the problem and coming up with solutions. In this particular instance, the food insecurity perceived to be caused by adverse effects of Climate Change. The solution to the food security problem thus involved exploring a menu of Climate-Smart Agriculture options for an open transdisciplinary inquest.

Two types of stakeholder were identified on site; the target group and the other stakeholders with an interest. The target group was the smallholder farmers by the fact that they were the ones directly affected by the problem and also the ones most likely to benefit in the event of success. The other stakeholders included an NGO- Caritas whose personnel had been on site on a similar mission (i.e. to help the local community improve food security by giving them drought escaping crop varieties). Their interest therefore was valid as lessons learnt would help them mold their programs in future. The ministry of Agriculture, represented by the area Agricultural extension officer was similarly an interested party. Their reconnaissance duties and provision of agronomic advice was anticipated to build momentum for the study. Additionally, the officer also being at the core of policy formulations for the agriculture sector at the sub county level was instrumental in spurring policy drift towards Climate-Smart Agriculture. The area chief, representing the local administration was another important stakeholder whose role couldn't be underestimated. His office was crucial in community profiling and as a key informant.

This study therefore was like thinking ahead of the newly launched Kenya Climate-Smart Agriculture Strategy-2017-2026. The CSA approach provided a mechanism for the local stakeholders to identify practical agricultural strategies suitable for their conditions. In the context in which it was employed, this study aimed at developing a Climate-Smart Agriculture model for Wiyumiririe through a transdisciplinary approach focusing on the first two pillars.

At Wiyumiririe the issue at hand was food insecurity which the community associated with the reduced and erratic rainfall. To determine the validity of such claims necessitated carrying out vulnerability assessments and getting the perceptions the farmers had towards climate change viewed from the lens of the observed historical weather data. Together with that, coping mechanisms already in use were captured and reevaluated to determine their efficacy as an entry point to identifying suitable CSA options for exploration. These choices were evaluated by individuals with an understanding of the local climate and food production to determine their worth for current and future weather conditions. The challenges and opportunities for bringing onboard all intellectual resources from academia, practice and traditions so as to amicably solve the problem through an iterative process was an important undertaking. At the core of it all was the urgency to develop a mode of inquiry that was all inclusive: scientifically robust and meets the needs for the target community, practitioners and other interested parties. The first task was teambuilding for the transdisciplinary study comprising of selected members from the community, key informants and experts from meteorology and soil science.

From the target community, systematic sampling was carried out to select farmers' representative for the transdisciplinary study. This sampling technique was effective in getting a sizable number of representatives but required to be applied methodically and with some level of affirmative action to capture households manned by single-parent and those who have been farming for more than 30 years. The researcher took into account the fact that if the sampling method was applied mechanically, it was bound to be biased and hence fails to capture special groups within the community. Therefore for systematic sampling method to work effectively it ought to be applied judiciously preceded by adequate sensitization. That notwithstanding, this study found it to be an effective tool in choosing participants compared to other methods. Key informants were purposively selected as the only appropriate method since they were sole holders of their respective offices and jurisdiction. The scientists were also purposively selected based on their knowledge and skills.

The sampled individuals were subjected to both personal interviews and focus group discussions to: assess their vulnerabilities to climate change; get their perceptions towards climate change; identify suitable CSA options for adaptation and be part of the group that was involved in on-farm trial. Focus group discussion was an outstanding tool for this study. First, it helped sharing of ideas among participants. Secondly, the urge by some participants to be seen as active made the discussion lively. Eventually, more information was generated that fostered innovativeness. The ability of the tool to allow participants mingle freely created an environment for social learning and building bridges for further interactions. This is what is required for a robust CSA intervention as the issue of food security and building resilience cannot be solved individually; rather it has to be done collectively and collaboratively. A chance of finding a food secure family amongst insecure ones or vice versa was unlikely. Therefore both the problem identification and corresponding solutions were better handled at the community level highlighting the importance of the two methods used for getting primary information from farmers.

This has implications for Climate-Smart Agriculture interventions. First the understanding of individual household food security needs is important as individuals within the community maybe affected differently. The variation in these needs has a bearing on how each individual farmer perceives Climate Change which may not necessarily be the same across board. Secondly, the mutual and collaborative learning experiences created during focus group discussions are paramount for effective CSA interventions. Given that not a single farmer lives in isolation or can be affected by extreme weather events singularly, the responsibility of finding a working formula to bring credible representatives together for knowledge sharing sessions was vital. This study demonstrated the use of focus group discussion in providing a viable option. While few farmers had managed to point out what was ailing food production systems in the locality during personal interviews, the gist of the matter came into be during focus group discussions. This means that for any robust CSA intervention to be realized, focus group discussions must be part of the process.

Transdisciplinarity embraces all forms and sources of knowledge production in a way that helps to crystallize the idea and transform the problem into a researchable topic. That came into force when the various stakeholders met during recursive sessions during the study. No one has the monopoly of knowledge and this study endeavored to embrace all validated forms of knowledge in a way that helped to conceptualize the problem at hand and concurrent solutions through a recursive process. It was during the incipient stages where there was teambuilding, problem identification and sharing of responsibilities. This was followed by the stage of knowledge production.

The relevance of the various stakeholders was fully realized during the inquest. Farmers played their role in providing their perceptions about climate change, highlighting the coping mechanism in place out and being willing participants for the field trials. The area chief who helped in community profiling was additionally relevant in identifying policy gaps which the study focused on. The Agricultural extension officer was a third pillar in problem identification and for hands-on solutions during the field trial. The meteorologist, the fourth pillar in providing information about the climate was crucial in helping the study have a better understanding of climatic trends for current and future. By embracing knowledge production from various sources, this study was able to capture the transdisciplinarity aspect of it.

The impacts of climate change to the food production systems at Wiyumiririe could not be fully understood by embracing only one source of knowledge or adopting a solely disciplinary approach. Primarily there were cross-cutting issues that required attention before arriving at the main problem of food insecurity. For instance, whereas effects of Climate Change were evident, the solution first required to assess the amount of climate vulnerabilities and capture the farmers view about climate change, i.e. whether they believed it was there or not and its implications for their food production. Likewise, even though the agricultural extension officer was aware of the best practices to adopt for enhanced crop production, he required information about the expected impacts of Climate change on crop yields, clear information on changing weather patterns among others. Moreover the study had anticipated to run a crop model which was only possible after collecting adequate information on current and historical weather data, soil, onset and cessation of rainfall to mention but a few which could only be sourced from other stakeholders.

Therefore, by forming the transdisciplinary team with defined roles for the various players, the study was on course crystallized around four objectives; determining the vulnerabilities of agricultural production system to climate change; the perceptions the farmers had towards climate change; determining the inter-annual and inter-seasonal weather variation for the study site; Calibrating, validation Aquacrop model as a basis for determining the effects of Climate change on sorghum yields and developing scenarios for policy makers.

The first task was to carry out vulnerability assessment for the target community. Given that the research problem was on food insecurity attributed to Climate Change, the focus here was to determine the amount of exposure for the agricultural production system to climatic related hazards, the corresponding levels of sensitivity and the adaptive capacity of the target community. Information gathered from focus group discussions and interview with key informants showed that the agricultural production system was exposed to the following climatic hazards: erratic and inadequate rainfall, early cessation of rains, droughts, sporadic high temperatures and frost bite. That being the case, the task of assessing crops' response to these hazards (sensitivity) was next. It emerged that of all the crops grown in the area, maize was the most prone to all these hazards. The amount of rainfall received was below average requirement for the crop. The very erratic nature of the rains made it impossible to determine the appropriate time for planting. Occasional mid-season cessation of rains exacerbated by periodic long dry spells implied that farmers hardly ever received any crop yields from maize. In other words, the crop production was highly sensitive to these climatic hazards.

Vulnerability of a system entails taking into the account the combined effects of exposure and sensitivity and adaptive capacity, the latter being in response to the first two. The evidence from this study was compelling. One, there was no weather advisory services to guide them on planting dates with respect to the unpredictability of the rainfall. Secondly, there was no effort to use drought tolerant crops in light of cessation of rainfall and prolonged dry spells. Third, the mechanisms for harvesting rain water were found wanting, and forth, there were no efforts to address high temperatures and their associated effects on crop growth especially with regard to water loss through evapotranspiration. And lastly, the efforts to alter planting dates to help crops escape from frost bite during the most susceptible stages was found missing. Hence this study concluded that the agricultural production system was highly vulnerable to the highlighted climatic hazards. Propelled by the need to make the community food secure, the task therefore shifted to finding plausible Climate-Smart Agriculture options for adaptation.

Results from resource mapping indicated that there were no nearby water bodies; the borehole sunk by the Kenya government was less than satisfactory in providing water. Rainwater harvesting technologies in use were inefficient and the prospects for piped water for irrigation were zero. Concurrently, even though the community and leaders were aware of the need to try drought tolerant crops, none of it was on trial. However, farmers in focus group discussion reiterated that if they were shown better ways of harvesting rain water, get drought tolerant crops, have measures to address declining soil fertility and get accurate information on rainfall pattern that would improve their adaptive capacity and consequently reduce their agricultural systems' sensitivity to climatic hazards. Against this milieu, stakeholders were engaged in coming up with suitable Climate-Smart Agriculture options for adaptation. To aid the process, two tools were put into use. First it was pair-wise ranking followed by Multi-criteria analysis, the outcome of which is presented in chapter four of this document. In the process, the role of farmers in profiling the problems that affect them and coming up with solutions came in handy. The study observed that it was the farmers who were at the forefront in suggesting rain water harvesting technologies such as use of Zai pits and preparation of land by double digging. Through elaborate and iterative discussions, it was argued that if farmyard manure was incorporated into those parcels and a drought tolerant crop like sorghum planted at the right time then, those options might somehow alleviate the chronic food shortage.

An understanding of historical weather pattern for Wiyumiriririe was also necessary primarily in: evaluating how it mirrored with farmers perceptions about climate change; giving insight into rainfall variability across seasons and determining the frequency and intensity of droughts and wet seasons. Rainfall Anomaly Index and Standardized Precipitation index were the tools identified for the historical weather pattern analysis. That information was a guide in choosing appropriate time for planting, selecting the seasons that were best suited for cultivation and gave advance knowledge about occurrence of droughts. It was also important for understanding the frequency and intensity of extreme weather events as well as in developing scenarios for future.

It was established in the study that these interventions required testing in a field trial and evaluating for current and future weather conditions. Hence running Aquacrop model was adopted to help determine the: validity of the prioritized options in harvesting rainwater and retaining it at the root zone to sustain crop growth; impacts of Climate Change on crop yields and to develop scenarios for policy makers.

The outcome of this study coming in era of the Kenya CSA strategy may serve as a reference with regard to the achievement of agenda four (especially food security) and realization of Kenya vision 2030. That is in harmony with the findings of a recent study by Makate, et al., (2019) which showed high agricultural productivity is achievable when a host of CSA options are used instead of just one. Globally there is consensus that for the world to feed the expected 9 billion people in the world by the year 2050, there is need to transit to Climate-Smart Agriculture (Taylor, (2018). However the underlying factors upon which CSA policy frameworks operate require consideration. This is because in the current situation it operates under diverse political landscapes which in most situations are only concerned with technical solutions at the farm production level (Taylor, (2018). The situation is not any different at Wiyumiririe. So the proposed CSA policy document must take into cognizant the county and national political orientation for it to thrive.

7.2 Conclusion and Recommendations

This study draws from Climate-Smart Agriculture though a transdisciplinary approach into the food security problems facing smallholder farmers of Wiyumiririe Laikipia County, Kenya. The population is dominated by smallholder farmers who practice subsistence farming that is purely rain fed. Given that climate has direct link to agriculture the scope for this study entailed to; get the vulnerabilities of the food production systems to climate change; capture the perceptions of farmers had towards climate change, analyze historical weather data and; calibrated and run Aquacrop model to determine the effects of Climate Change on crop yields and prepare scenario for policy makers. Results indicated that the food production system was indeed vulnerable to Climate Change. Since the system was solely rain fed the situation was precarious as the rains were inadequate, erratic and declining with time. The unpredictability in the onset of rains, long dry spells, cessation of rains and frost bite were the major handicaps to crop production.

From the analysis of historical weather data for the past 60 years, the study established evidence of Climate Change and variability. The total amount of rainfall was declining; droughts were becoming regular and more intense while at the same time the wet periods were reducing both in number and intensity. This evidence was corroborated by farmers in focus group discussions. However most perceived climate change to be a local phenomenon which could be addressed by curbing deforestation and restricting cultivation along river valleys. The use of the two meteorological indices RAI and SPI was important in two aspects. One by showing rainfall variability across and within seasons; it's possible to establish guidelines for cropping systems depending on the growth habit and importance of a crop. Secondly by showing the frequency and intensity of both droughts and wet seasons, it's easier to predict the occurrence of the two extreme weather events in way crops can escape from the former and benefit from the latter. However future studies should focus on how the two indices can be used to determine the onset and cessation of rains so as to properly guide the appropriate time for planting.

The study managed to calibrate and validate Aquacrop for Sorghum growing at Wiyumiririe in 11 treatments under investigation. That included all treatments where the Zai pits and double digging was done as micro-catchment technologies for harvesting rainwater. However for conventional farming with less than 5tons of manure applied calibration wasn't possible because of inadequate biomass production. For the treatments calibrated the model was able to simulate canopy cover, biomass and soil water content to satisfactory levels. Therefore the simulated yields more or less reflected field observations. However, observed yields were generally higher than simulated ones perhaps because the variety of sorghum used in the crop file is different from the Seredo variety cultivated. Developing calibration parameters for local cultivars as opposed to relying on those parameterized elsewhere may improve the model. The model could further be improved by establishing a soil fertility file to aid calibration since this study found mere visual observations not adequate. Moreover, the local varieties of sorghum have a high tendency for tillering, so calibration that takes into considering that aspect of Sorghum should be done. Compared to conventional farming the intervention for double digging and Zai pits were effective in retaining water at the root zone that was sufficient enough to ensure that crops under those regimes did not experience water stress. That was a huge success for Climate-Smart Agriculture and with the empirical evidence from Aquacrop, the possibility of up scaling is real. In the same vein, Aquacrop was able to simulate the effects of Climate change on Sorghum yields. The findings from this study concur to previous ones in which Sorghum yields are predicted to increase in the future. But that should be taken with caution as discussed in the previous section. In terms of food security and resilient to climate change , the way to go is for the farmers to embrace double digging and use of farm yard manure at 2.5tons/ha or more. Zai pits were good but the prospects for water logging rendered the option second best.

All in all, the study showed the transdisciplinary approach to be an effective method for solving complex food security problems associated with climate change. What made the approach superior was its ability is to help the actors grasp the complexity of a problem, to accommodate the diversity of views and scientific perceptions of the problem in order to develop knowledge and practices for the common good. It was found important to carryout out a vulnerability assessment and determine the perceptions farmers had towards climate change to correctly grasp the issue at hand. Similarly Aquacrop proved to be a useful tool in predicting yields and developing scenarios for policy makers.

Consequently, this study inferred that for the target community to be food secure and build resilience to climate change, then they need to put into policy and practice the interventions explored, more so the use of either double digging or Zai pits, where substantial amount of farmyard manure has been incorporated together with the use of a drought resistant Sorghum variety like (Seredo).By running simulations for future weather conditions, this study demonstrated that the same interventions would work for future and the farmers would continue to achieve good Sorghum crops yields both in the medium term (2038) and in the long term (2068). This is because, the technologies used were found to be effective in holding sufficient amount of water at the root zone that was adequate to sustain healthy crop with minimal water and temperature stress.

7.3: Recommendations

1. Climate-Smart model policy document for Wiyumiririe that embraces, transdisciplinarity, double digging and/or construction of Zai pits, use of farm yard manure, drought tolerant crops and crop modeling using Aquacrop be prepared and put into practice.

2. Concurrent to CSA policy, a robust monitoring and evaluation tool be developed
3. In the absence of clear guidelines from the ministry of agriculture on planting dates, sowing should be made when at least 20mm of rainfall has been received during the last seven days prior.
4. To improve weather advisory services, downscaled weather for specific sites be done using Marksim weather generator and data validated.
5. Aquacrop model calibration could be improved by
   i. Creating a soil fertility similar to that one of soil profile
   ii. Creating a platform for calibrating crops with tillering and ratoon potential
6. A robust rain fed CSA intervention should comprise of the following core ingredients.
   i. Transdisciplinary approach
   ii. Vulnerability assessment
   iii. Uses effective PRA tools such as Focus group discussions.
   iv. Puts into practice knowledge what is co-produced by societal and scientific discourses.
   v. Performs analysis of rainfall variability to aid prediction of the onset, amount and cessation of rains as well as determine frequency and intensity of both drought and wet seasons.
   vi. Develops scenarios for future weather conditions under climate change

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APPENDICES

APPENDIX I. PROFILE OF FARMERS SAMPLED FOR THE STUDY

Divided into three Focus Group Discussions							
	Names	Gender	Marital status	Highest Education	F/Size	Age	Meals/ Day
1	George Nudge	M	Married	8	5	71	1
2	Moses Thong	M	Married	8	6	53	1
3	Joyce Nyokabi	W	Married	8	7	47	1
4	Monica Wanjiru	W	Married	Form 2	4	45	1
5	Paul kimani	M	Married	8	5	38	2
6	Lucy Wanjiku	W	Married	7	8	53	1
7	Joseph Njoroge	M	Married	7	6	53	2
8	David Gikonyo	M	Married	Diploma	4	40	3
9	Elizabeth Wanjiru	W	Widow	7	9	76	1
10	Mary Njambi	W	Widow	No Education	7	72	2
11	Susan Wangari	W	Married	8	6	39	2
12	Paul Wachira	M	Married	7	2	59	1
13	Elizabeth Njoki	W	Married	7	6	48	1
14	Esther Wangari	W	Single	7	6	48	2
15	Anne Muthoni	W	Single	Form 1	2	19	2
16	Rahab Njoki	W	Single	7	5	45	1
17	Charles Wangombe	M	Married	Form 2	4	49	2
18	John Muthee	M	Married	Form 3	6	44	4
19	Joseph Wambugu	M	Married	8	3	31	3
20	Hannah Wanjiku	W	Single	8	4	30	2
21	Rebecca Wanjiku	W	Single	7	5	35	2
22	Daniel karani	M	Married	Form 2	4	35	2
23	Jacqueline Wangari	W	Married	7	7	51	1
24	Beth Wanjiru	W	Married	Form 4	2	27	2
25	Dorcas Waithera	W	Married	8	5	45	2
26	Geoffrey Kimani	M	Married	Form 4	4	41	2
27	Elijah Waweru	M	Married	8	3	32	2
28	Irene Nduta	W	Married	Form 4	6	43	2
29	Simon Mbugua	M	Married	Form 4	4	54	2
30	Elizabeth Muthoni	W	Singe	Form 3	3	39	2

APPENDIX II: HISTORICAL WEATHER DATA (RAINFALL)

Rainfall data from 1958 to 2017 (60 years).														
Year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Average	Totals
1958	65.3	52.8	76.7	54.6	110	48	82.6	11.2	18	59.4	38.1	166.9	65.3	783.6
1959	53.8	25.4	60.7	23.6	101.9	19.3	62.7	6.1	7.9	69.3	111.3	38.1	48.341666 67	580.1
1960	66.5	13.7	131.8	82.8	16.8	3.6	11.2	67.6	25.9	85.9	47	96.8	54.13333	649.6
1961	22.9	28.4	138.4	147.8	57.9	2	4.3	79	264.9	368.3	342.9	101.6	129.8667	1558.4
1962	141. 7	22.9	59.7	85.1	95.8	38.1	23.6	20.6	51.6	135.6	104.6	122.2	75.125	901.5
1963	94.7	52.3	56.9	181.9	123.4	7.6	6.4	54.9	0	42.9	256.5	210.3	90.65	1087.8
1964	8.6	47.5	57.2	226.8	30.2	43.4	55.4	67.3	78.5	70.6	63.5	117.9	72.24167	866.9
1965	101. 9	8.6	46	108	24.1	41.1	9.4	10.2	7.4	35.8	76.2	23.6	41.025	492.3
1966	16.5	31.2	142.2	96	40.1	38.6	24.1	75.9	0	61.2	104.9	4.3	52.91667	635
1967	29.5	29.5	117.1	144.8	81.3	18.3	62.7	20.8	19.8	140.5	135.1	6.4	67.15	805.8
1968	0	149.9	163.1	206	29.2	44.2	13.7	2.8	0	81.5	197.6	111.5	83.29167	999.5
1969	81.3	148.1	155.2	89.9	0	82.3	0	37.8	84.6	60.2	96.8	82.8	76.58333	919
1970	94.2	0	129.5	139.4	46.2	21.8	20.3	14	12.4	18.5	126.2	17	53.29167	639.5
1971	51.6	0	36.1	157.5	41.7	10.4	8.6	154.4	25.7	41.4	89.4	109.2	60.5	726
1972	59.7	71.6	40.1	24.1	43.9	69.6	8.9	11.2	41.7	102.6	59.7	36.1	47.43333	569.2
1973	49.8	32.3	43.2	74.7	7.1	6.9	40.4	30	61.2	33	129.8	39.6	45.66667	548
1974	28.2	39.6	66.5	147.3	20.1	0	43.9	75.7	2	30.2	117.6	26.4	49.79167	597.5
1975	29	43.4	103.1	78.2	16.5	77.2	56.9	56.9	61	50	88.1	30.5	57.56667	690.8
1976	0	93.7	41.4	96.8	64.8	12.7	69.6	23.9	16.5	38.1	92.5	130.3	56.69167	680.3
1977	46	101.9	47.2	144.8	52.1	22.9	83.1	26.4	7.4	31.2	166.9	61	65.90833	790.9
1978	66.5	183.9	135.6	39.1	17.5	7.9	33.8	36.6	54.6	84.3	74.2	214.1	79.00833	948.1
1979	157. 7	115.3	69.6	64	43.4	7.4	16.5	22.4	44.7	71.6	156.7	15.2	65.375	784.5

1980	9.9	29.5	101.3	68.3	54.5	14.2	0	0	18.3	90.2	90.2	39.2	42.96667	515.6
1981	39.6	48.8	56.9	47.5	132.8	0	134.9	21.8	36.6	74.7	67.8	115.6	64.75	777
1982	32.5	17.5	33.5	154.2	36.1	31.2	0	59.9	15.7	169.4	161.8	86.1	66.49167	797.9
1983	3.3	84.3	29.2	90.4	0	45.5	67.3	66.5	14.2	53.1	28.2	104.4	48.86667	586.4
1984	14.7	23.1	74.2	51.8	0	0	6.1	0	57.4	136..7	149.9	69.6	40.61818	446.8
1985	71.4	75.4	133.9	69.9	24	0	36.8	0	72.4	131.1	86.6	51.3	62.73333	752.8
1986	29.6	8.1	59.2	121.9	21.3	36.8	58.2	21.3	10.4	36.3	401.3	77.2	73.46667	881.6
1987	38.4	31.5	43.4	112.3	46.7	66.3	4.8	12.7	26.9	33	152.7	78.2	53.90833	646.9
1988	42.4	69.9	103.1	153.7	0	83.6	88.6	54.6	43.7	84.8	118.9	179.3	85.21667	1022.6
1989	31.8	78	91.9	153.9	0	0	78	31	39.6	89.7	140.2	94.7	69.06667	828.8
1990	75.2	91.7	148.8	110.5	93.2	4.6	4.1	41	14	12.2	61.2	61	59.79167	717.5
1991	43.9	39.9	117.3	114	25.4	97.5	6.1	105.7	0	15	59.4	85.6	59.15	709.8
1992	59.2	43.2	22.9	110	119	0	0	0	0	48.8	109.5	120.4	52.75	633
1993	196.9	80.3	45.5	18.5	33.5	66.8	3	8.6	0	104.4	103.4	56.1	59.75	717
1994	0	13.2	106.2	111.3	19.6	41.9	27.9	50.3	25.4	69.6	261.6	26.9	62.825	753.9
1995	14.5	40.4	90.4	74.7	74.7	37.3	28.2	28.4	50	72.6	80.3	110.5	58.5	702
1996	35.6	45.2	39.1	69.9	7.4	128.3	27.7	71.9	4.3	70.6	177.5	73.9	62.61667	751.4
1997	35.8	0	95.8	158.2	31	20.8	109.7	51.6	0	96.3	239	107.7	78.825	945.9
1998	248	63.5	167.9	79.2	94.2	41.1	20.8	58.7	10.4	90.7	46.7	40.6	80.15	961.8
1999	52.3	18.8	139.4	0	0	0	0	0	0	18.5	155	29	34.41667	413
2000	37.5	3	46.5	82	30.5	17	19.5	20.5	13.5	24.7	77.1	60.1	35.99167	431.9
2001	73	54.6	66.5	74	3.5	44	5.5	8.2	31	66.5	194	34.8	54.63333	655.6
2002	59.8	2	119.1	133.4	166.2	6.5	4	0	7.5	38.6	136	85.8	63.24167	758.9
2003	49.5	12	83.3	198.5	120.9	18.5	13.5	186.7	0	70.3	154.8	74.4	81.86667	982.4
2004	137.2	41.4	89	129.7	98	2	42.9	16.7	12.6	75.2	64.3	23	61	732
2005	76.7	0	117.2	117.8	82	9.7	0	27	124.5	45	153.6	32.5	65.5	786
2006	54.9	63.3	134.6	80.8	73.8	6.5	0	76	4.6	21.6	149.7	133.7	66.625	799.5

2007	72.5	46.6	40.4	153.6	33.5	99.9	123.2	79.7	108.3	169.8	161.8	14	91.94167	1103.3
2008	71.8	8.9	84.6	69.3	9.4	2.5	41.1	10.1	65.9	43.6	141	32.9	48.425	581.1
2009	54	5	55.9	33.7	59.4	15.7	0	0	14.1	42.7	55	190.7	43.85	526.2
2010	20.5	16.9	42.3	126.4	51.4	21.2	53.7	43.2	14.8	128.1	153.7	49.6	60.15	721.8
2011	11.6	26.4	75.2	60.3	50.5	80.3	113.4	78.7	63.8	140.3	133.4	54.1	74	888
2012	0	24.3	1.2	144.5	75.4	23.6	89.9	203.1	65.1	126.5	30.3	116.5	75.03333	900.4
2013	58	23	52.6	143.8	7.8	50.8	114.5	30.2	97.9	20	104.5	76.8	64.99167	779.9
2014	2.2	58.3	122.5	145.5	2.7	18.1	45.4	20.8	87.5	38.8	80.8	155.8	64.86667	778.4
2015	9.2	59.5	83.2	118.8	5.7	12.7	18.8	2.2	16.5	79.4	149.1	83.3	53.2	638.4
2016	153.5	15.5	58.4	145.6	71.8	60.1	33	18.4	44.9	27.3	106.9	120	71.28333	855.4
2017	8.7	25.3	24.4	51.2	96.9	20.9	35.7	69.2	16.3	15.1	191.4	129.5	57.05	684.6
Average	54.85	44.67167	81.90167	104.8717	48.61333	30.82	36.57333	41.34	35.23167	71.97627	126.73667	80.61	63.13947	756.9967
Total	3291	2680.3	4914.1	6292.3	2916.8	1849.2	2194.4	2480.4	2113.9	4246.6	7604.2	4836.6	3788.368182	45419.8

APPENDIX III: GENERATED RAINFALL DATA FROM 2010 TO 2068

Generated rainfall data from 2010 to 2049											
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	January	37	37	38	38	38	38	38	39	39	39
2	February	38	38	38	38	38	38	38	38	39	39
3	March	76	76	76	76	76	76	76	76	76	76
4	April	112	112	112	112	112	112	113	113	113	113
5	May	69	69	69	69	69	69	69	69	69	69
6	June	44	44	44	44	44	44	44	44	44	44
7	July	77	77	77	77	77	77	77	77	77	77
8	August	79	79	79	78	78	78	78	78	78	78
9	September	44	44	44	44	44	44	44	44	43	43
10	October	58	58	58	59	59	59	59	59	60	60
11	November	113	114	114	114	115	115	115	116	116	116
12	December	84	84	85	85	85	85	85	85	85	86
	Average	69.25	69.33333	69.5	69.5	69.58333	69.58333	69.66667	69.83333	69.91667	70
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
1	January	39	40	42	42	42	42	42	41	41	41
2	February	40	39	41	41	41	42	41	39	39	40
3	March	75	76	75	76	76	76	76	76	77	77
4	April	116	113	114	115	115	115	115	114	115	115
5	May	70	69	64	64	64	64	64	68	68	68
6	June	46	44	43	43	43	43	43	44	44	44
7	July	77	77	77	77	77	77	77	77	77	77
8	August	81	78	78	78	78	78	78	79	79	79

9	September	43	43	41	41	41	41	41	43	43	43
10	October	65	60	59	59	60	60	60	61	61	62
11	November	117	117	115	116	116	117	116	119	120	120
12	December	86	86	85	86	86	86	86	87	87	87
	Average	71.25	70.16667	69.5	69.83333	69.91667	70.08333	69.91667	70.66667	70.91667	71.08333
		2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
1	January	41	42	42	42	42	42	43	43	43	43
2	February	40	40	40	40	40	40	40	40	41	41
3	March	77	77	77	77	77	77	77	77	77	77
4	April	115	115	115	115	116	116	116	116	116	117
5	May	68	68	68	68	68	68	68	68	68	68
6	June	44	44	44	44	44	44	44	44	43	43
7	July	77	77	77	77	77	77	77	77	77	77
8	August	79	79	79	79	79	79	79	79	79	79
9	September	42	42	42	42	42	42	42	42	42	42
10	October	62	62	62	62	62	62	62	62	62	63
11	November	120	121	121	121	121	122	112	122	123	123
12	December	87	88	88	88	88	88	89	89	89	89
	Average	71	71.25	71.25	71.25	71.33333	71.41667	70.75	71.58333	71.66667	71.83333
		2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
1	January	43	43	44	44	44	44	44	44	44	45
2	February	41	41	41	41	41	42	42	42	42	42
3	March	77	77	77	77	77	77	77	77	77	77
4	April	117	117	117	117	117	118	118	118	118	118
5	May	67	67	67	67	67	67	67	67	67	67

6	June	43	43	43	43	43	43	43	43	43	43
7	July	77	77	77	77	77	77	77	77	77	77
8	August	79	79	79	79	79	79	79	79	79	79
9	September	42	42	42	42	42	42	42	42	42	42
10	October	63	63	63	63	63	63	63	63	63	63
11	November	123	124	124	124	125	125	125	125	126	126
12	December	89	90	90	90	90	91	91	91	91	92
	Average	71.75	71.91667	72	72	72.08333	72.33333	72.33333	72.33333	72.41667	72.58333
		2050	2051	2052	2053	2054	2055	2056	2057	2058	2059
1	January		55	55	55	55	56	55	55	55	55
2	February		56	56	56	56	57	57	57	57	57
3	March		112	112	112	112	114	112	113	113	113
4	April		142	142	142	142	147	142	143	143	143
5	May		53	53	52	52	53	52	52	52	52
6	June		30	30	30	30	31	30	30	30	30
7	July		31	31	31	31	30	31	31	31	31
8	August		36	36	36	36	35	36	36	36	36
9	September		29	29	29	29	29	29	29	29	29
10	October		80	80	80	80	81	80	80	80	79
11	November		142	142	143	143	144	143	144	144	144
12	December		78	78	79	79	79	80	80	80	81
	Average										
		2060	2061	2062	2063	2064	2065	2066	2067	2068	
1	January	55	56	56	55	56	56	56	56	56	
2	February	57	58	58	58	58	58	58	59	59	

3	March	113	113	113	113	113	113	114	114	114	
4	April	143	143	143	143	144	144	144	144	144	
5	May	52	52	52	52	52	52	52	52	52	
6	June	30	30	30	29	29	29	29	29	29	
7	July	31	31	31	31	31	31	31	31	31	
8	August	36	36	36	36	36	36	36	36	35	
9	September	29	29	29	29	30	30	30	30	30	
10	October	79	79	79	79	79	79	79	79	79	
11	November	145	145	145	145	146	146	146	147	147	
12	December	81	81	82	82	82	83	83	83	84	
	Average										

APPENDIX IV: GENERATED TEMPERATURE DATA FROM 2010 TO 2068

	2010		2011		2012		2013	
Year	Max	Min	Max	Min	Max	Min	Max	Min
January	25.1	6.8	25.2	6.8	25.2	6.8	25.2	6.8
February	24.9	7.9	24.9	7.9	24.9	7.9	24.9	7.9
March	23.9	9.8	23.9	9.8	24	9.8	24	9.9
April	23.1	9.5	23.2	9.5	23.2	9.6	23.2	9.6
May	22.6	8.4	22.7	8.4	22.7	8.4	22.7	8.5
June	21.5	8.6	21.5	8.6	21.5	8.7	21.5	8.7
July	21.5	8.4	21.5	8.4	21.5	8.4	21.6	8.5
August	23.2	7.7	23.2	7.8	23.2	7.8	23.2	7.8
September	23.4	8.2	23.4	8.2	23.5	8.2	23.5	8.2
October	23.2	8.9	22.2	8.9	22.2	8.9	22.2	8.9
November	23.4	7.7	22.5	7.7	22.5	7.7	22.5	7.7
December	23.25455	8.354545	23.10909	8.363636	23.12727	8.381818	23.13636	8.409091
Average	23.25455	8.354545	23.10909	8.363636	23.12727	8.381818	23.13636	8.409091
	2014		2015		2016		2017	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.2	6.5	24.4	6.5	24.4	6.6	22.4	6.6
February	25.2	6.8	25.2	6.9	25.2	6.9	25.3	6.9
March	25	8	25	8	25	8	25	8
April	24	9.9	24	9.9	24	9.9	24	10
May	23.2	9.6	23.3	9.6	23.3	9.7	23.3	9.7
June	22.7	8.5	22.8	8.5	22.8	8.5	22.8	8.6
July	21.6	8.7	21.6	8.7	21.6	8.8	21.6	8.8
August	21.6	8.5	21.6	8.5	21.6	8.5	21.6	8.5
September	23.3	7.8	23.3	7.8	23.3	7.9	23.3	7.9
October	23.5	8.3	23.5	8.3	23.5	8.3	23.6	8.3
November	22.2	8.9	22.2	9	22.2	9	22.3	9
December	22.5	7.7	22.5	7.8	22.5	7.8	22.5	7.8
Average	23.25	8.266667	23.28333	8.291667	23.28333	8.325	23.14167	8.341667
	23.17083	8.413889	23.19028	8.440972	23.19028	8.46875	23.20347	8.486806
	2018		2019		2020		2021	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.4	6.6	24.5	6.6	24.4	6.5	24.5	6.7
February	25.3	6.9	25.3	6.9	25.1	6.9	25.3	7
March	25	8	25.1	8.1	25	8.1	25.1	8.1
April	24.1	10	24.1	10	23.9	9.8	24.1	10.1
May	23.3	9.7	23.3	9.7	23.1	9.5	23.4	9.8

June	22.8	8.6	22.8	8.6	22.5	8.4	22.9	8.7
July	21.6	8.8	21.7	8.8	21.4	8.6	21.7	8.9
August	21.7	8.6	21.7	8.6	22.4	8.4	21.7	8.6
September	23.3	7.9	23.4	7.9	23.2	7.8	23.4	8
October	23.6	8.4	23.6	8.4	23.4	8.5	23.6	8.4
November	22.9	9	22.3	9	22.2	9	22.3	9.1
December	22.5	7.8	22.6	7.8	22.5	7.8	22.6	7.9
Average	23.375	8.358333	23.36667	8.366667	23.25833	8.275	23.38333	8.441667
	23.28958	8.504861	23.27222	8.513889	23.16319	8.422917	23.29028	8.586806
	2022		2023		2024		2025	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.4	6.8	24.5	6.8	24.5	6.8	24.5	6.9
February	25.3	7	25.3	7	25.3	7.1	25.3	7.1
March	25.2	8.2	25.2	8.2	25.2	8.2	25.2	8.2
April	24.2	10.1	24.2	10.2	24.2	10.2	24.2	10.2
May	23.6	9.8	23.6	9.9	23.6	9.9	23.6	9.9
June	23	8.7	23	8.8	23.1	8.8	23.1	8.8
July	21.8	8.9	21.8	9	21.8	9	21.8	9
August	21.8	8.7	21.8	8.7	21.8	8.8	21.8	8.8
September	23.5	8.1	23.5	8.1	23.6	8.1	23.6	8.1
October	23.8	8.5	23.8	8.5	23.8	8.5	23.8	8.6
November	22.4	9.2	22.4	9.2	22.4	9.2	22.5	9.2
December	23.6	8	22.6	8	22.6	8	22.6	8
Average	23.55	8.5	23.475	8.533333	23.49167	8.55	23.5	8.566667
	2026		2027		2028		2029	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.5	6.9	24.5	6.8	24.5	6.8	24.5	6.8
February	25.3	7.1	25.4	7.1	25.4	7.1	25.5	7.1
March	25.2	8.2	25.2	8.2	25.2	8.3	25.3	8.3
April	24.2	10.2	24.2	10.2	24.2	10.2	24.2	10.2
May	23.7	9.9	23.5	9.9	23.5	9.9	23.6	9.9
June	23.1	8.8	23	8.8	23.1	8.8	23.1	8.9
July	21.8	9	21.8	9	21.9	9	21.9	9
August	21.8	8.8	21.9	8.8	21.9	8.8	21.9	8.8
September	23.6	8.1	23.5	8.1	23.6	8.1	23.6	8.2
October	23.8	8.6	23.8	8.3	23.8	8.6	23.8	8.6
November	22.5	9.2	22.4	9.2	22.4	9.2	22.4	9.2
December	22.6	8.1	22.7	8	22.7	8	22.7	8.1
Average	23.50833	8.575	23.49167	8.533333	23.51667	8.566667	23.54167	8.591667

	2030		2031		2032		2033	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.6	6.9	24.6	6.9	24.6	6.9	24.6	6.9
February	25.5	7.2	25.5	7.2	25.5	7.2	25.5	7.2
March	25.3	8.3	25.3	8.3	25.3	8.3	25.3	8.4
April	24.3	10.3	24.3	10.3	24.3	10.3	24.3	10.3
May	23.6	10	23.6	10	23.6	10	23.7	10
June	23.1	8.9	23.1	8.9	23.2	8.9	23.2	9
July	21.9	9.1	21.9	9.1	21.9	9.1	22	9.1
August	22	8.8	22	8.9	22	8.9	22	8.9
September	23.6	8.2	23.6	8.2	23.7	8.2	23.7	8.3
October	23.8	8.6	23.8	8.6	23.9	8.7	23.9	8.7
November	22.5	9.3	22.5	9.3	22.5	9.3	22.5	9.3
December	22.7	8.1	22.7	8.1	22.7	8.1	22.8	8.1
Average	23.575	8.641667	23.575	8.65	23.6	8.658333	23.625	8.683333
	2034		2035		2036		2037	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.6	7	24.6	7	24.6	7	24.7	7
February	25.6	7.2	25.6	7.3	25.6	7.3	25.6	7.3
March	25.4	8.4	25.4	8.4	25.4	8.4	25.4	8.5
April	24.3	10.4	24.3	10.4	24.4	10.4	24.4	10.4
May	23.7	10.1	23.7	10.1	23.7	10.1	23.8	10.1
June	23.2	9	23.2	9	23.3	9	23.3	9.1
July	22	9.2	22	9.2	22	9.2	22.1	9.2
August	22.1	8.9	22.1	9	22.1	9	22.1	9
September	23.7	8.3	23.7	8.3	23.8	8.3	23.8	8.4
October	23.9	8.7	23.9	8.7	24	8.8	24	8.8
November	22.5	9.4	22.5	9.4	22.6	9.4	22.6	9.4
December	22.8	8.2	22.8	8.2	22.8	8.2	22.8	8.2
Average	23.65	8.733333	23.65	8.75	23.69167	8.758333	23.71667	8.783333
	2038		2039		2040		2041	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.7	7.1	24.7	7.1	24.7	7.1	24.7	7.1
February	25.6	7.3	25.6	7.4	25.7	7.4	25.7	7.4
March	25.5	8.5	25.5	8.5	25.5	8.5	25.5	8.5
April	24.4	10.5	24.4	10.5	24.1	10.5	24.5	10.5
May	23.8	10.2	23.8	10.2	23.8	10.2	23.9	10.2
June	23.3	9.1	23.3	9.1	23.4	9.2	23.4	9.2
July	22.1	9.3	22.1	9.3	22.1	9.3	22.2	9.3
August	22.2	9	22.2	9.1	22.2	9.1	22.2	9.1

September	23.8	8.4	23.8	8.4	23.9	8.4	23.9	8.5
October	24	8.8	24	8.8	24.1	8.9	24.1	8.9
November	22.6	9.4	22.6	9.5	22.6	9.5	22.7	9.5
December	22.8	8.3	22.9	8.3	22.9	8.3	22.9	8.3
Average	23.73333	8.825	23.74167	8.85	23.75	8.866667	23.80833	8.875
	2042		2043		2044		2045	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.8	7.2	24.8	7.2	24.8	7.2	24.8	7.2
February	25.7	7.4	25.7	7.4	25.8	7.5	25.8	7.5
March	25.6	8.6	25.6	8.6	25.6	8.6	25.6	8.6
April	24.5	10.6	24.5	10.6	24.5	10.6	24.6	10.6
May	23.9	10.3	23.9	10.3	23.9	10.3	24	10.3
June	23.5	9.2	23.5	9.2	23.5	9.3	23.5	9.3
July	22.2	9.4	22.2	9.4	22.3	9.4	22.3	9.4
August	22.3	9.2	22.3	9.2	22.3	9.2	22.4	9.2
September	24	8.5	24	8.5	24	8.5	24	8.6
October	24.1	8.9	24.1	8.9	24.2	9	24.2	9
November	22.7	9.6	22.7	9.6	22.7	9.6	22.7	9.6
December	22.9	8.4	22.9	8.4	22.9	84	23	8.4
Average	23.85	8.941667	23.85	8.941667	23.875	15.26667	23.90833	8.975
	2046		2047		2048		2049	
	Max	Min	Max	Min	Max	Min	Max	Min
January	24.8	7.3	24.8	7.3	24.9	7.3	24.9	7.3
February	25.8	7.5	25.8	7.6	25.8	7.6	25.9	7.6
March	25.6	8.7	25.7	8.7	25.7	8.7	25.7	8.7
April	24.6	10.7	24.6	10.7	24.6	10.7	24.6	10.7
May	24	10.4	24	10.4	24.1	10.4	24.1	10.4
June	23.5	9.3	23.6	9.3	23.6	9.4	23.6	9.4
July	22.3	9.5	22.3	9.5	22.4	9.5	22.4	9.6
August	22.4	9.3	22.4	9.3	22.4	9.3	22.5	9.3
September	24	8.6	24.1	8.6	24.1	8.7	24.1	8.7
October	24.2	9	24.3	9	24.3	9.1	24.3	9.1
November	22.8	9.6	22.8	9.7	22.8	9.7	22.8	9.7
December	23	8.5	23	8.5	23	8.5	23	8.5
Average	23.91667	9.033333	23.95	9.05	23.975	9.075	23.99167	9.083333
	2050		2051		2052		2053	
	Max	Min	Max	Min	Max	Min	Max	Min
January			26.3	7.5	26.3	7.5	26.3	7.6

February			26.2	8.4	26.9	8.4	27.3	8.4
March			26.8	9.3	26.8	9.3	26.9	9.4
April			26.2	12.2	26.2	12.2	26.3	12.2
May			26.1	12.6	25.3	12.6	26.2	12.6
June			25.3	11.3	25.4	11.4	25.4	11.4
July			24.1	11.8	24.1	11.8	24.1	11.8
August			24.4	11.1	24.4	11.1	24.4	11.1
September			26.7	11.2	26.7	11.2	26.7	11.2
October			26.7	11.3	26.8	11.3	26.8	11.3
November			24.6	10.6	24.6	10.7	24.6	10.7
December			24.5	8.6	24.5	8.6	24.5	8.6
Average								

	2054		2055		2056		2057	
	Max	Min	Max	Min	Max	Min	Max	Min
January	26.4	7.6	26.6	7.7	26.4	7.6	26.4	7.7
February	27.3	8.4	27.4	8.5	27.4	8.5	27.4	8.5
March	26.9	9.4	27.1	9.6	27.0	9.4	27.0	9.5
April	26.3	12.3	26.5	12.3	26.4	12.3	26.4	12.3
May	26.2	12.7	26.3	12.7	26.3	12.7	26.3	12.8
June	25.4	11.4	25.6	11.6	25.5	11.5	25.5	11.5
July	24.1	11.9	24.3	12.0	24.2	11.9	24.2	12.0
August	24.5	11.2	24.7	11.4	24.5	11.3	24.6	11.3
September	26.7	11.4	26.9	11.4	26.8	11.2	26.8	11.3
October	26.8	11.7	26.9	11.4	26.9	11.3	26.9	11.4
November	24.2	10.7	24.8	10.8	24.7	10.8	24.7	10.8
December	24.6	8.7	24.8	8.7	24.6	8.7	24.6	8.8
Average								
	2058		2059		2060		2061	
	Max	Min	Max	Min	Max	Min	Max	Min
January	26.5	7.7	26.5	7.7	26.5	7.7	26.5	7.8
February	27.4	8.6	27.4	8.6	27.4	8.6	27.5	8.6
March	27.0	9.5	27.0	9.5	27.5	9.5	27.1	9.6
April	26.4	12.4	26.4	12.4	26.5	12.4	26.5	12.4
May	26.3	12.8	26.4	12.0	26.4	12.8	26.4	12.3
June	25.5	11.5	25.6	11.5	25.6	11.6	25.6	11.6
July	24.3	12.0	24.3	12.0	24.3	12.0	24.4	12.1
August	24.6	11.3	24.6	11.3	24.7	11.4	24.7	11.4
September	26.9	11.3	26.9	11.4	26/9	11.4	27.0	11.4
October	26.9	11.5	27.0	11.5	27.0	11.5	27.0	11.5
November	24.8	10.8	24.8	10.9	24.8	10.9	24.8	10.9

December	24.6	8.8	24.7	8.8	24.7	8.8	24.7	8.9
Average								
	2062		2063		2064		2065	
	Max	Min	Max	Min	Max	Min	Max	Min
January	25.6	7.8	26.6	7.8	26.6	7.9	26.6	7.9
February	27.5	8.7	27.5	8.7	27.5	8.7	27.6	8.8
March	27.1	9.6	27.1	9.6	27.2	9.7	27.2	9.7
April	26.5	12.5	26.5	12.5	26.6	12.5	26.6	12.6
May	26.4	12.8	26.5	12.9	26.5	12.9	26.5	13.0
June	25.7	11.6	25.7	11.7	25.7	11.7	25.7	11.7
July	24.4	12.1	24.4	12.1	24.5	12.2	24.5	12.2
August	24.7	11.4	24.7	11.4	24.8	11.5	24.8	11.5
September	27.0	11.5	27.0	11.5	27.0	11.5	27.1	11.5
October	27.1	11.6	27.1	11.6	27.1	11.6	27.1	11.7
November	24.9	10.9	24.9	11.0	24.9	11.0	24.9	11.0
December	24.7	24.7	24.8	8.9	24.8	8.9	24.8	9.0
Average								
	2066		2067		2068			
	Max	Min	Max	Min	Max	Min		
January	26.7	7.9	26.7	8.0	26.7	8.0		
February	27.6	8.8	27.6	8.8	27.6	8.8		
March	27.2	9.7	27.2	9.7	27.2	9.8		
April	26.6	12.6	26.7	12.6	26.7	12.6		
May	26.6	13.0	26.6	13.0	26.6	13.1		
June	25.8	11.7	25.8	11.8	25.8	11.8		
July	24.8	12.2	24.5	12.3	24.6	12.3		
August	24.8	11.5	24.9	11.6	24.9	11.6		
September	27.1	11.6	27.1	11.6	27.2	11.6		
October	27.2	11.7	27.2	11.7	27.2	11.7		
November	25.0	11.0	25.0	11.1	25.0	11.1		
December	24.8	9.0	24.8	9.0	24.7	9.0		
Average								

APPENDIX V: METEOROLOGICAL INDICES

	Standardized precipitation index		
Year	SPI Yearly Index	Drought intensity	Intensity of wetness
1958	0.213	0	0
1959	-1.023	0.032933683	0
1960	-0.572	0	0
1961	3.568	0	2.57759512
1962	0.833	0	0
1963	1.712	0	0.722359368
1964	0.657	0	0
1965	-1.649	0.65907489	0
1966	-0.664	0	0
1967	0.335	0	0
1968	1.309	0	0.319099226
1969	0.921	0	0
1970	-0.635	0	0
1971	-0.112	0	0
1972	-1.097	0.106968808	0
1973	-1.244	0.253785697	0
1974	-0.907	0	0
1975	-0.32	0	0
1976	-0.383	0	0
1977	0.254	0	0
1978	1.064	0	0.073576668
1979	0.218	0	0
1980	-1.476	0.485883225	0
1981	0.177	0	0
1982	0.292	0	0
1983	-0.981	0	0
1984	-1	0.010034484	0
1985	0.041	0	0
1986	0.733	0	0
1987	-0.589	0	0
1988	1.417	0	0.426761363
1989	0.458	0	0
1990	-0.162	0	0
1991	-0.207	0	0
1992	-0.676	0	0
1993	-0.165	0	0
1994	0.048	0	0
1995	-0.253	0	0
1996	0.034	0	0

1997	1.053	0	0.062875816
1998	1.13	0	0.139850879
1999	-2.285	1.294980831	0
2000	-2.126	1.136175238	0
2001	-0.534	0	0
2002	0.076	0	0
2003	1.228	0	0.238352452
2004	-0.077	0	0
2005	0.227	0	0
2006	0.301	0	0
2007	1.781	0	0.790932609
2008	-1.016	0.026189148	0
2009	-1.399	0.408874278	0
2010	-0.137	0	0
2011	0.765	0	0
2012	0.828	0	0
2013	0.193	0	0
2014	0.185	0	0
2015	-0.642	0	0
2016	0.598	0	0
2017	-0.357	0	0

Year	**Rainfall Anomaly Index (long rainfall season)**		
	RAI seasonal index	Drought intensity	Intensity of wetness
1958	1.717	0	0.727267081
1959	-0.818	0	0
1960	-1.338	0.348010405	0
1961	1.183	0	0.19310559
1962	-0.011	0	0
1963	1.824	0	0.834099379
1964	2.738	0	1.748385093
1965	-1.754	0.764217247	0
1966	0.95	0	0
1967	3.017	0	2.026645963
1968	3.812	0	2.821677019
1969	0.612	0	0
1970	1.352	0	0.362049689
1971	-1.146	0.156460665	0
1972	-2.747	1.757438121	0
1973	-3.086	2.09560618	0
1974	-0.591	0	0
1975	0.723	0	0

1976	-0.413	0	0
1977	1.176	0	0.185652174
1978	-1.629	0.638882232	0
1979	-2.409	1.419270061	0
1980	-1.525	0.534830522	0
1981	1.722	0	0.732236025
1982	-1.13	0.139906984	0
1983	-1.664	0.674354406	0
1984	-4.036	3.046260445	0
1985	-0.903	0	0
1986	-0.127	0	0
1987	-0.692	0	0
1988	3.136	0	2.145900621
1989	0.522	0	0
1990	1.451	0	0.461428571
1991	1.429	0	0.439068323
1992	-1.203	0.213216144	0
1993	-3.204	2.21384676	0
1994	0.102	0	0
1995	0.063	0	0
1996	-0.718	0	0
1997	2.8	0	1.810496894
1998	2.495	0	1.504906832
1999	-3.864	2.873629198	0
2000	-2.537	1.546969888	0
2001	-2.584	1.59426612	0
2002	3.141	0	2.150869565
2003	3.278	0	2.287515528
2004	1.461	0	0.47136646
2005	0.594	0	0
2006	-0.167	0	0
2007	3.673	0	2.682546584
2008	-2.267	1.277381365	0
2009	-3.265	2.275331862	0
2010	-0.184	0	0
2011	1.911	0	0.921055901
2012	0.791	0	0
2013	1.658	0	0.667639752
2014	0.781	0	0
2015	-1.504	0.513547217	0

2016	1.643	0	0.652732919
2017	-1.742	0.752393189	0

Year	**Rainfall Anomaly Index (Short rainfall season)**	
	RAI seasonal index	Drought intensity
1958	-0.401	0
1959	-1.547	0.556773812
1960	-1.271	0.281019317
1961	9.074	0
1962	1.397	0
1963	3.908	0
1964	-0.712	0
1965	-3.63	2.639973678
1966	-2.758	1.76758673
1967	0.027	0
1968	1.878	0
1969	-1.018	0.027826553
1970	-2.976	1.985683467
1971	-1.013	0.022812835
1972	-2.056	1.065666198
1973	-1.955	0.965391836
1974	-2.662	1.672326087
1975	-2.803	1.812710193
1976	-0.489	0
1977	-0.534	0
1978	1.571	0
1979	-0.925	0
1980	-1.524	0.53421208
1981	-0.559	0
1982	2.333	0
1983	-2.374	1.384037296
1984	1.292	0
1985	-0.286	0
1986	3.995	0
1987	-0.414	0
1988	1.749	0
1989	0.753	0
1990	-3.66	2.670055987
1991	-3.018	2.028300071
1992	-0.043	0
1993	-0.414	0
1994	1.324	0
1995	-0.426	0

1996	0.709	0
1997	2.771	0
1998	-2.567	1.577065443
1999	-1.953	0.962884977
2000	-2.971	1.980669749
2001	0.254	0
2002	-0.501	0
2003	0.325	0
2004	-2.956	1.965628595
2005	-1.236	0.24592329
2006	0.419	0
2007	1.111	0
2008	-1.577	0.58685612
2009	0.136	0
2010	0.869	0
2011	0.808	0
2012	-0.178	0
2013	-1.983	0.992967285
2014	-0.125	0
2015	0.535	0
2016	-0.657	0
2017	0.948	0

APPENDIX VI: PHOTOGRAPHS

A. Focus group discussions

B. Sorghum Crop in the field