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Research Article

Application of Aquacrop Model for Sorghum Yield Projections and Scenarios Development under Rainfed Farming at Wiyumiririe Laikipia County, Kenya

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Abstract: The current study used an Aquacrop driven Climate-smart Agriculture approach to investigate how future climatic conditions will affect the yields of Sorghum cultivated under rainfed agriculture. There were three parcels of land prepared by; double digging, Zai pits and conventional farming on which varying levels of farmyard manure was incorporated. The field trials were set out in a split plot design with the main interventions as the major factors and levels of manure as minor factors in a trial that run for several cropping seasons from January 2016 to February 2019. In due course Aquacrop model was calibrated and validated. The model output formed a basis of understanding the impacts of Climate Change on Sorghum crop yields and developing scenarios for policy makers. Results showed that 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 that purported increase in yields needs to be taken with causation. The reason being that the compounding effects of water stress which the model predicts to cause a 61% reduction in canopy expansion, 31% closure in stomata and temperature stress of 31% are not yet fully understood.
Keywords: Aquacrop model, double digging, Zai pits, Emission scenarios.

INTRODUCTION

Climate change and variability is of immediate concern to farmers and if no measures are taken to ameliorate its effects it is likely to disrupt food production systems in the tropics. According to (Lobell, 2015), the changes to the climate system have already been experienced in form rising temperatures, variability in rainfall, frequent droughts and typhoons. Yet, global consensus on the mitigation of greenhouse gases has been elusive (Sharma, 2015) and the policy makers for developed countries especially USA have shrugged of the whole notion of climate change (Amaranth and Tripath 2016). Nevertheless member countries of the European Union recognized effects of climate change and subsequently adopted measures to reduce its impacts. In spite of that, (Fussel, 2015) observed that slow mitigation responses will not ameliorate adverse effects of greenhouse gases that are already in the atmosphere to significantly reduce global warming. Hence alongside rapid mitigation measures, adaptation to climate change is required.

A Study done by (Bharat and Onkar 2012) revealed global warming and climate change will have adverse effects to both physical and biological systems in most continents across the globe. In the past 30 years climate change is associated to global agricultural decline by (1-5) % per decade with dire consequences to the status of global food security and worse in Sub-Saharan Africa (Adger et al., 2013). Undoubtedly these climatic

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changes are likely to deepen the vulnerability of the agricultural sector especially food production. Already many farmers in Sun-Sahara Africa (SSA) are vulnerable to risks in Agriculture which makes it difficult for them to attain food security (Hertel and Rosch, 2010: MacDowell and Hess 2012: Thornton et al., 2008). Climate is likely to make a bad situation worse by exacerbating the risks they face. Recent studies have showed that the East African region has been experiencing frequent episodes of both excessive (Webster *et al.*, 1999) and deficit rainfall (Hastenrath *et al.*, 2007: Williams and Funk 2011) coupled by an increase in seasonal mean temperatures. According to (Waithaka *et al.*,2013) these negative effects of climate change are likely to be felt more in Kenya mainly because of reliance on rainfed agriculture, a high population growth rate of approximately 3.7% that has not been matched by a corresponding increase in economic growth which has resulted to endemic poverty that affects more than 50% of the population. The situation is likely to be worse for the smallholder farmers of Wiyumiririe Laikipia County who solely depend on rainfed agriculture, are dearth of resources and practice subsistence farming. Preliminary survey of the area showed that there were no tangible measures that could significantly improve their food production and build resilience to Climate change. For instance the mechanisms to harvest rainwater were ineffective while measures to address soil fertility were lukewarm. Irrigated agriculture was absent and there was no weather advisory service.

The Food and Agriculture Organization of the United Nations proposed Climate-Smart Agriculture approach as a plausible avenue for addressing challenges brought by Climate change anchored on three pillars of; increasing agricultural production, adaptation and reducing greenhouse gas emissions where possible (FAO,2010). This study investigated how a menu of climate-smart Agriculture premised on the first two pillars; increasing food production and; adaptation would perform in addressing food security and building resilience for the smallholder farmers of Wiyumiririe. As much as increasing current food production is important, the future crop yields in a changing climate is equally paramount, more so for smallholder farmers like those in this study who solely depend on rainfed Agriculture. Therefore, predicting yield is gaining momentum so as to optimize the limited rainwater available for increased crop production. The response by FAO has been splendid by providing Aquacrop model that among other applications is capable of simulating yield response to water. In this study, Aquacrop was calibrated, validated and used to determine the effects of Climate change on sorghum crop yields cultivated under double digging and Zai pits. Aquacrop model is a product of the Food and Agriculture Organization (FAO) of the United Nations developed to simulate crop yields response to water stress and soil fertility as a field management practice (Steduto *et al.*, 2009). It's a progression from the previous Doorembos and Kassam (1979) approach that separated crop transpiration (To) from soil evaporation (Eo). The model describes how a crop growing out in the field interacts with the soil and the atmosphere (Fig 1).The model uses few parameters that are explicit and intuitive but without necessarily compromising on accuracy, which makes it simple and robust (Steduto *et al.*, 2009). The parameters are either readily available or require simple methods to determine (FAO, 2017). Crop development is a product of 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, then 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 and reference evapotranspiration 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 (Steduto *et al.*, 2009).Therefore it is a single canopy growth and senescence model that forms the basis for estimating crop transpiration (Tr). The model considers the final yield as a function of biomass (B) and harvest index (HI). Further it separates the effects of water stress into; canopy expansion, stomata closure, canopy senescence and harvest index (Steduto *et al.*, 2009). The heart of the model is the relationship B=WP*(Tr); where WP* is the normalized water productivity, a conservative crop parameter that contributes to the robustness and generality of the model (Steduto et.al. 2007).

Aquacrop model calculates crop yields in four steps; (step 1, Crop development) (step 2, crop transpiration), (step 3 biomass production) and (step 4, crop yields) (Figure 1).

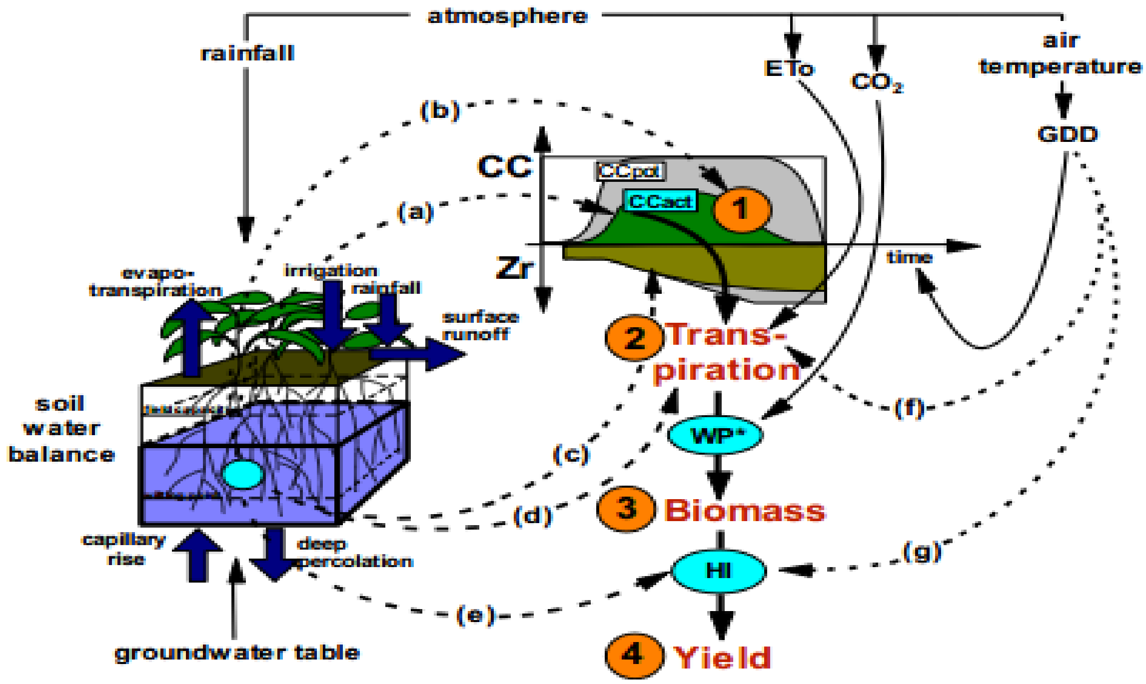

Figure 1: Calculation scheme of Aquacrop. The dotted arrows are processes affected by water stress i.e.; (from a to e) and those affected by temperature stress (from f to g). (Source: FAO, 2017).

The same four steps are considered in evaluating the simulated results. The model has wide applications such as; Generating biomass and crop yield for a given environment; Developing a performance indicator which 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; Calculating irrigation water requirements; Analysing yield gaps; preparing scenarios for policy makers and ; Calculating the effects of climate change on food production, which is the focus of this study.

Double digging is a farming practice that entails digging deeper than usual about 60cms or twice the normal cultivation, followed by incorporating a variety of manures in the soil (Machinga 2007). At the beginning it is labour intensive but once the beds are ready, they remain fertile for a long duration of time such that one doesn't have to dig again for 3-4 years. The other benefits include; higher yields up to four times compared to the normal cultivation; keeps the soil fertile for a long time; allows plant roots to grow deeper; keeps the soil light and soft for a long time; Improves soil aeration, drainage and; soil water holding capacity (Machinga, 2007).

Zai pits involve making holes that are usually 60cms deep with a square or circular base of about 50cms wide. The pits are then filled with soil that has been mixed with organic manures (Barry *et al.*, 2008). The benefits associated with Zai pits are; increased yields; enhancing uptake of Nitrogen, phosphorus and potassium by plants; improving water efficiency and soil water holding capacity (Barry *et al.*, 2008).

To date no study to determine the effects of Climate change on sorghum crop cultivated under rainfed agriculture for parcels of land prepared by double digging and Zai pits has been reported in literature. In that case some of the previous studies that applied; double digging, Zai pits and Aquacrop model are presented as follows Studies done by (Miriti et al.,(2003) investigated how double digging, addition of mulch and compost manure affected soil physical properties as well as growth and yields of sunflower in central Kenya. The findings indicated that double digging improved soil physical properties as drainage and yields were significantly higher than the conventional cultivation. Barry *et al.*,(2008) investigated construction of Zai pits alongside others; contour and stone bunds; systems of inter-row water harvesting and; straw mulching and construction of semi-circular half-moons as micro-catchment techniques for harvesting rain water in West Africa. Results of that study showed that Zai pits were effective micro-water technology that significantly improved millet crop yields and soil water holding capacity. Moreover, the technology improved nutrient uptake by plants. Sandile *et al.*, (2017) tested Aquacrop model in simulating yield responses for three Sorghum genotypes using the minimum data input in South Africa. Results showed a good agreement between observed and simulated soil water content and canopy cover for all the three Sorghum genotypes. Nevertheless, the study found out the model had overestimated biomass and yields perhaps a carryover from the model insensitivity to water stress which the study observed to be less than satisfactory. Xin-liang *et al.*,(2014) assessed Aquacrop model in simulating irrigated winter wheat canopy cover, biomass and grain yield in North China plain. Results showed that the model data for calibration was consistent with model data for validation. Moreover, good relationships were found between observed and simulated data for canopy cover, biomass and grain yield across the four seasons. Likewise, Farahani *et al.*, (2009) and Garcia-Vila *et al.*,(2009) investigated Aquacrop model for cotton under full and deficit irrigation in Syria and Spain respectively. Results indicated that the model prediction of reference evapotranspiration, total biomass, yield and soil water across the four levels of irrigation were promising, putting into consideration the simplicity of the model and limited parameterization. Nevertheless, the study pointed out that key parameters such as normalized water productivity, canopy cover and total biomass for calibration ought to be tested under different climate, soil, cultivars, irrigation methods and field management. In another study, Greets *et al.*,(2009), Todorovic *et al.*,(2009) and Hsiao *et al.*,(2009), applied Aquacrop model in determining the effects of varying quantities of irrigation water for Quinoa, corn, sunflower and maize respectively. All the findings indicated that the model presented a new approach for scenario analysis that provides a good balance between robustness and output precision.

The divided loyalty at the global level on how to tackle climate change coupled by the understanding that no mitigation measures can effectively reverse the amount of greenhouse gases already present in the atmosphere necessitates the focus to be on adaptation, more so for vulnerable farming communities like those in this study. Their reliance on climate sensitive parameters of rainfall and temperatures, endemic poverty puts them into a precarious position in terms of exposure to climatic hazards and prone to food insecurity. There being no irrigation on site, the task of effectively harvesting rainwater was an important problem this study sought to solve. Together with the issue of soil fertility provided the impetus for this study. Adaptation options require to be properly investigated to ensure they resonate with the ideals and aspirations of the community in a way that will make them food secure and resilient to Climate change. Consequently, this study purposed to investigate whether;1 The interventions for double digging and Zai pits together with the addition of farmyard manure would significantly increase sorghum crop yields for the smallholder farmers of Wiyumiririe and; Aquacrop model would simulate sorghum crop yields for current and future weather conditions in way that would inform policy makers. The main features of the model considered were: 1 Soil water content simulation 2.Canopy cover simulation. 3 Biomass simulations. 4. Yields simulations for current and future weather conditions under RCP 8.5, RCP 6.0, RCP 4.5 and RCP 2.6.

MATERIALS AND METHODS

The study site was situated at Shalom, Wiyumiririe Laikipia County. Wiyumiririe location (study site) is situated in Ngobit ward which is about 80kms South-west of Nanyuki town and borders Nyeri and Nyandarua counties. The ward covers approximately 40 square kilometers with a population of approximately 368,686 persons in 6760 households with a population density of 564persons per square kilometer. Most of the residents are found in Wiyumiririe and Nyambugichi locations. Ngobit ward is within Laikipia East constituency, Laikipia County. The ward is comprised of five locations; Wiyumiririe, Nyambugichi, Mwituria, Ngobit and Sirima. The main source of livelihood is mixed farming. Crop cultivated are; spring onions, maize, Irish potatoes, beans, 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 use up a lot of nitrogen and perhaps nitrogen losses through volatilization. There's plenty of farmyard manure available from farmers' fields, and farmers are continuously sensitized on its potential benefits in improving soil fertility, soil water holding capacity, ameliorating soil acidity and moderating soil temperatures. Interview with the area agricultural extension officer indicated that majority of the farmers who had adopted the practice of using farm yard manure in their farms have recorded increased crop yields.

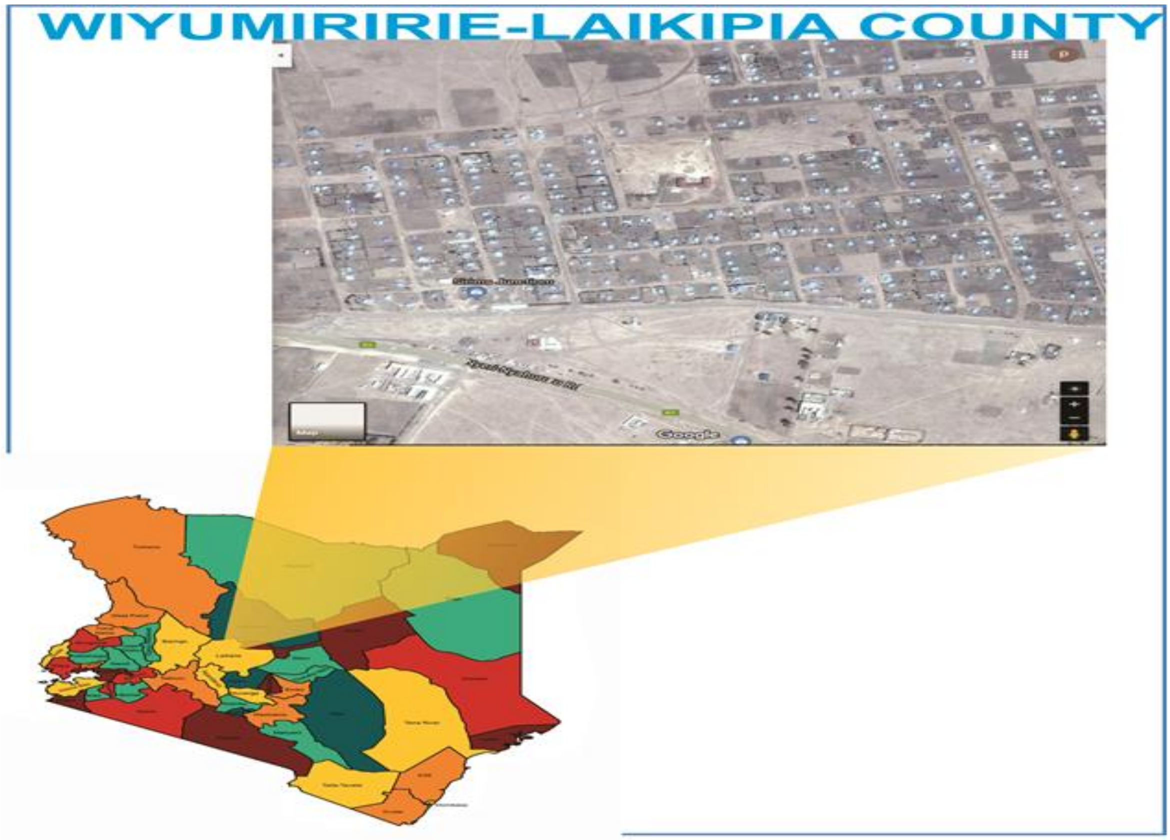

Figure2. ***The red icon indicates the experimental plot; the blue are the households of the target population. Adopted from MarkSim@GCM-DSSAT weather generator***

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 growth during the 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

Split Plot Experimental Design.

A. Treatment plots where Zai pits were done.

1\2	0	1	1\4	3\4	1\4	0	1\2
3\4	1	0	1\2	1	3\4	1\4	0
1\4	3\4	1\2	1	1\4	0	1	3\4
3\4	1\4	1	3\4	0	1\2	1\4	1
0	1\2	3\4	1\4	1\2	1	3\4	1\4
3\4	0	1\2	1	3\4	1\4	1\2	3\4
0	1	1/2	1\4	1\2	1	3\4	1\4
1	1\2	3\4	0	1\4	3\4	0	1\2
3/4	0	1	1\4	0	1\4	1\2	1
1	1\2	0	1\2	1	3\4	1\4	0
1\4	1	1\2	0	3\4	1\2	1	1\4
0	1\4	3\4	1	1\2	3\4	1\2	0

3\4	1\2	1	0	

B. Treatment plots where double digging was done.

3\4	0	1	1\2	1\4	0	1	3\4	1\4	1\2

C. Treatment plots for conventional farming

1\4	1/2	1	3/4	0	1/4	1	3\4	0	1/2

Where: 1 represents full rates (5tons/ha), ¾ (3.75tons/ha), ½ (2.5tons/ha), ¼(1.25tons/ha) and 0 no manure applied, the unfertilized control.

The site was cleared from vegetation and subdivided into three equal portions. On one section, land preparation was done by double digging, the other section 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, filling back the previously dug portion one and 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 other 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 administered twice randomly. 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 the residual effect.

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) the short rains to allow a ratoon crop in the following (March-July) long rains Upon On maturity in February the crop is harvested and immediately ratooned to take advantage of the long rainfall season which starts mid-march. Ratooning has benefit to the farmer in that it is possible to have more than one harvest per year. A ratoon crop has advantages inform of faster establishment, reduced labour requirements and its early maturity helps 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.

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 ministry of Agriculture guidelines and historical weather data, the date for planting was arrived at and coincided to 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.

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 in both long and short rainfall season. Its crop development was found to be 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 results 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; Raes *et al.*, 2012). Acceptable pattern of parameters was obtained by adjusting parameters within practical physical ranges. The parameters to be calibrated first were for soil following 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 process using experimental data obtained from the 2018 cropping.

Climate Data

Climate data was of two categories; observed and generated weather data. The observed weather data was mainly for model calibration and validation while generated was for simulating future sorghum crop yields. The observed weather data was for the period January 2016 to February 2019, while generated comprised of daily weather data for the period January 2016 to December 2068 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.

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 model 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 files for each treatment. To calibrated 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.

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 the crop file. 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 reach physiological maturity and harvest index 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 (CCo=0.4167%). I.e. CCo=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 per treatment were taken every fourteen days at a perpendicular height 1.5meters above the crop using Canopeo software installed in an Ipad, 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 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^oC 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 average yields were divided by biomass at harvest time.

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 The Pearson Correlation Coefficient (r) The root mean square (RMSE), Normalized Root Mean Square Error CV(s) and The Nash-Sutcliffe model efficiency coefficient (EF), that were employed for that purpose.

RESULTS AND DISCUSSION

Calibration and Validation Process

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

Climatic Parameters

The model output for the monthly rainfall totals for the period (January 2016 to February 2019) is as shown in Figure 3. 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 as collaborated by farmers in focus group discussions.

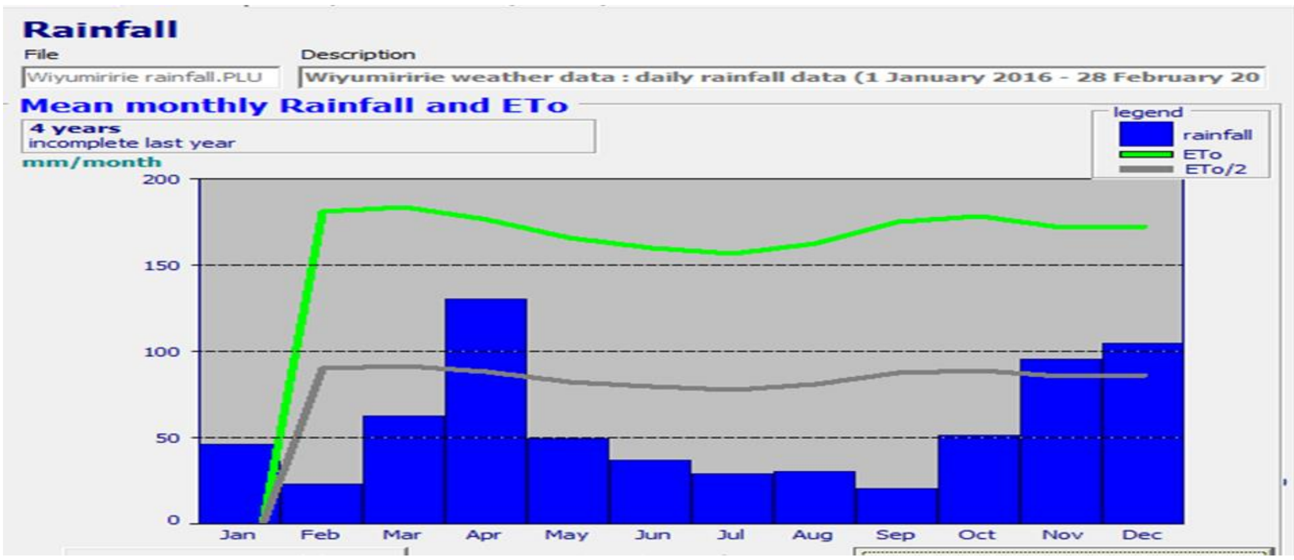

Figure 3: Mean Monthly Rainfalls from January 2016 to February 2019

The onset of rains during the March 2016 season delayed substantially accounting for the late planting on April 5^{th}, when 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 in October 6^{th} 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 1.

Table 1: 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

Current Yields

The observed and simulated yields are as shown in table 6.4. Calibration for yields entailed determining the harvest index by dividing the yields by the biomass at harvesting. Results indicated that for higher yields the harvest index 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 wasn't significant. Part of the variation could be due experimental errors and calibration process which for most parameters was through trial and error (Hsiao et al., 2009; Raes et .al., 2012). That notwithstanding, the high agreement for goodness of fit between observed and simulated results for most treatments was encouraging.

Table 2: 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, yields that 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 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. Non limiting soil fertility conditions were not investigated in the current study probably to avoid scorching effects that is often associated with high quantities of farmyard manure.

The trend in the yields could partly be explained from effectiveness of the prioritized micro-catchment technologies for harvesting rainwater and the quantities of farmyard manure to their impact to improving soil water holding capacity and reducing soil fertility stress. Crops under all treatments experienced a 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 reduction in canopy expansion, stomata closure or trigger early senescence.

However at lower rates of farmyard manure, various forms of water stress were recorded. Thirty days after planting observed 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, while under conventional farming only 0.012tons/ha of biomass had formed, almost (76% less) primarily because of water stress that caused 54% reduction in canopy expansion and 3%. closure of stomata.

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 a 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% and 1% reduction in canopy development and 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 reduction in canopy expansion by 43% and 19% closure of stomata. By 2068 the stresses will cause 50% reduction in canopy expansion and stomata closure by 22%. 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 a 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.

For 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% and 0% reduction in canopy expansion and stomata closure 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 a temperature stress of 31% and water stress that will cause 36% reduction in canopy expansion and 20% stomata 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 to similar studies (Chipanshi et all., 2003; Turner and Rao 2013; Sultan et al., 2013; Chijioke and Haile 2011; Gwimbi et al., 2013) However these results may require to be taken with caution because the full effects of increased temperature to crop physiology, soil chemical characteristics, prevalence of pests and crop diseases are not yet fully understood. Table 3 shows the yield projections based on the four IPCC scenarios.

Table 3: 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

Scenarios for Policy Makers

This study Aquacrop was investigated on how it can help develop 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 manage 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 mitigate 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 are 2.792tons/ha and Zai pits 2.316tons/ha which are 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 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 concerns for the residents.

CONCLUSION

From this study it is evident if farmers continue to follow the conventional farming they may never harvest adequate crop yields in the foreseeable future. Meaning that, they might remain food insecure and vulnerable to climate change. The climate smart-

Agriculture interventions investigated, i.e. Double digging, Zai pits accompanied by varying levels of farmyard manure are promising in addressing food security and consequence building resilience by the farmers for current and future weather conditions, hence this study recommends their adoption. While that is being sought, the apparent increase in sorghum yields under climate change should be taken with caution as the full impact of anticipated water and temperature stress is not yet fully understood. Moreover, the compounding effects of pest and disease attacks and perhaps impacts of elevated soil temperatures on flora and fauna and; soil chemical properties are still obscure.

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