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A climate-smart agriculture approach using double digging, Zai pits and Aquacrop model in rain-fed sorghum cultivation at Wiyumiririe location of Laikipia County, Kenya

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ABSTRACT

The smallholder farmers of Wiyumiririe in Laikipia County are food insecure and highly vulnerable to climate related hazards owing to dearth of resources and over reliance on rain-fed agriculture. A preliminary reconnaissance pre-field visit of the area showed that there were no tangible CSA measures in place that could significantly improve the farmers' adaptive capacity in a way that would make them food secure. This study therefore sought to investigate how double digging, Zai pits and Aquacrop model would be applied to help the community overcome food insecurity and adapt to climate change. The researcher identified experimental plots that were set out based on the split plot design. The field trials were done from January 2016 to February 2019. Daily weather data, soil water content, above ground biomass and percent canopy cover measured at regular intervals formed input data to calibrate Aquacrop model. The validated model was then used to determine the impacts of climate change on Sorghum crop yields at Wiyumiririe and to prepare scenarios for policy makers. The findings show that the interventions had significant impact because farmers who adopt either double digging or Zai pits and farmyard manure at 5 tons/ha, can obtain yields of approximately 9tons per hectare under current weather conditions and in future under climate change. This is because the attainable yields of 9 tons/ha are more than double the average production in Kenya of 4 tons/ha. Furthermore, the model output showed sorghum crop yields will generally increase in future 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.

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1. Introduction

Climate change and variability are of immediate concern and if no measures are taken to ameliorate their effects, they are likely to disrupt food production systems in the tropics. According to [1] the changes to the climate system have already been experienced in form of rising temperatures, variability in rainfall, frequent droughts and typhoons. Yet, global consensus on the mitigation of greenhouse gases has been elusive [2] and the policy makers for developed countries especially USA have shrugged off the whole notion of climate change [3]. Nevertheless, member countries of the European Union recognized effects of climate change and subsequently adopted measures to reduce its impacts. In spite of that [4] 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 by [5] revealed that climate change has adversely affected both physical and biological systems in most continents across the globe. In the past 30 years [5] observed that climate change alone had contributed to global agricultural decline by (1-5) % per decade with dire consequences for global agricultural sector, more so, in Sub-Saharan Africa [6]. Undoubtedly these climatic changes are likely to deepen the vulnerability of the agricultural sector especially food production.

Already many farmers in Sub-Sahara Africa (SSA) are vulnerable to risks in Agriculture that makes it difficult for them to attain food security [7], [8] and [9]. Climate change 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 [10], and deficit rainfall coupled by an increase in seasonal mean temperatures [11]. According to [12] these negative effects of climate change are likely to be felt more in Sub Saharan countries including Kenya, mainly because of their reliance on rain-fed agriculture. The situation is likely to be worse for the smallholder farmers of Wiyumiririe Laikipia County because of the fragile nature of the ecosystem they live and lack of resources to ameliorate extreme weather events such as droughts. Furthermore, observation of the site 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. Therefore, the absence of weather advisory service affected sorghum cultivation in that farmers were unable to decide the best time for planting or the most suitable variety of crop to plant. At times when early planting was done, seeds failed to germinate and repeated gapping was expensive for the farmers. In other, situations when farmers practiced late planting, rains ceased before the crops had reached physiological maturity leading to loss of harvest. In that regard, exploration for appropriate micro-catchment technologies for rainwater harvesting was paramount.

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 [13]. Adaptation has invariably been equated to adjustments or moderation in natural or human systems in response to actual or anticipated climate changes and; the way communities are better equipped to cope with uncertainty in future by taking appropriate measures to minimize the adverse effects of climate change. The way communities adapt is a product of how in the first instance they are endowed to deal with negative climatic effects [14], [15] and [16]. 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 [15]. In order to improve food production and make the community resilience to Climate Change, the capacity and skills of Smallholder farmers in such regions require to be strengthened on innovative adaptation [17], defined as home-grown or assimilated practices that are capable of being applied to specific locations to aid in food production.

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 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. 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. This paper examined how CSA interventions of; double digging, Zai pits and Aquacrop model were used to determine current and future yields for rainfed sorghum crop at Wiyumiririe in a way that can inform policy makers how to address food security for the target smallholders' farmers.

2. Materials and Methods

In this section, the climate-smart agriculture interventions adopted for the current study are outlined.

2.1 Double Digging, Zai Pits and AquaCrop Modelling

Double digging is a farming practice that entails digging deeper than usual, about 60 cm or twice the normal cultivation of approximately 30 cm, followed by incorporating a variety of manures in the soil [18]. 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 does not have to dig again for 3-4 years. The other benefits of double digging include: higher yields up to four times compared to the normal cultivation; 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 [18].

Zai pits involve making holes that are usually 60 cm deep with a square or circular base of about 50 cm wide. The pits are then filled with soil that has been mixed with organic manures [19]. The benefits associated with Zai pits are: increase in yields; enhancing uptake of Nitrogen, phosphorus and potassium by plants; improving water use efficiency and soil water holding capacity [20].

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 [21]. It's a progression from the previous approach that separated crop transpiration (T_o) from soil evaporation (E_o) [22]. In the end, there was a single canopy growth and senescence model that forms the basis for estimating crop transpiration (T_r) [23]. The model considers the final yield as 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 [23]. By separating crop transpiration from soil evaporation, the model managed to avoid the compounding effects of non-consumptive use of water, an important consideration in situations where there is incomplete ground cover [23]. That gave rise to the equation:

$$B = WP . \sum Tr. \quad (1)$$

Where WP is the normalized water productivity, which is a conservative crop parameter that contributes to the robustness and generality of the model [23].

Aquacrop 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. This study investigated how Aquacrop model could be employed to inform improved Sorghum crop yields to aid food production in order to improve production and building resilience for the smallholder farmers of Wiyumiririe.

Several studies have been conducted concerning application of double digging, Zai pits and Aquacrop model. The study by [23] showed that double digging improved soil physical properties such as drainage, and crop yields were significantly higher than the conventional cultivation practices. Zai pits were found to be an effective micro-water technology that significantly improved millet crop yields and soil water holding capacity [19]. Moreover, the technology improved nutrient uptake by plants [19]. Aquacrop has been parameterized, calibrated and validated for a number of crops including Sorghum and in wide geographical locations for both rainfed and irrigated agriculture [24-31]. From the articles reviewed, the general findings were that simulated data for canopy cover, above ground biomass and soil water content were in harmony with the observed field data save for few exceptions. For instance, [24] observed that simulated values for soil water content and crop canopy cover for all the three Sorghum genotypes were in agreement with the observed values. Nevertheless, the model overestimated biomass and yields, perhaps because of the inherent carryover error from the model insensitivity to water stress, which the study observed as unsatisfactory. Likewise, [27, 29] observed that model predictions of reference evapotranspiration, total biomass, yield, and soil water content across the four levels of irrigation were unsatisfactory owing to the oversimplification of the model and its limited parameterization. To avert this shortcoming, these studies recommended 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 other studies [29-31], it was evident the model presented a new approach for scenario analysis that provided a good balance between robustness and output precision.

In the Kenyan context, Aquacrop too has been applied. According to [28], 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. While according to [29], the model overestimated biomass but gave correct simulations for percent canopy cover and yields. Further, [30] 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. In Aquacrop, crop yields are calculated in four steps; Canopy development; crop transpiration; biomass production and; crop yields. Each of those steps can be affected by water and temperature stress.

2.2 Canopy Development

In simulating canopy development, Aquacrop describes expansion of canopy cover, which is above ground, as well as the root expansion. Unlike other crop models, which use leaf area index, Aquacrop uses the green canopy cover (CC), which is 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 soil surface covered by the green canopy. The value ranges from zero on bare soils to one when we have full canopy. It is normally expressed in percentage, from 0% to 100%.

In Aquacrop, canopy expansion from emergence to full development for non-limiting conditions follows a sigmoid curve designed with an exponential function for the first half of development and an exponential decay function for the second half according to the following equations:

$$CC = CC_O e^{CGC \cdot t}. \quad (2)$$

$$CC = CC_X - (CC_X - CC_0).e^{-CGCt}. \quad (3)$$

Crop development is available in Aquacrop and is described with the help of few parameters such as; time to reach maximum cover, onset and duration of flowering, time to senescence and time to reach physiological maturity. In the crop file, the user specifies the planting density, which determines the initial canopy cover (CCo), and the maximum cover (CC_x) that can be reached. The maximum canopy cover is reached in crop development stage and is described in Aquacrop with the help of a canopy growth coefficient (CGC). In later stages, canopy will decline and the help of canopy decline coefficient (CDC) describes that. In other words, Canopy development for non-limiting conditions is described in Aquacrop by CC_o, $CC_{x,}$ CGC, CDC and the time to reach a development stage, i.e. time for seedling emergence, time to maximum canopy cover, time to beginning of senescence and time to reach physiological maturity. All these are available in crop file. However, the user needs to tune these parameters to the variety and the environment in which the crop is cultivated. In the simulation, canopy development is adjusted according to water stress, which in Aquacrop is described by stress coefficients Ks. Ideally Ks is a modifier of its model parameter and the values range from one (1) when stress is non-existent zero (0) under full stress (Figure 1).

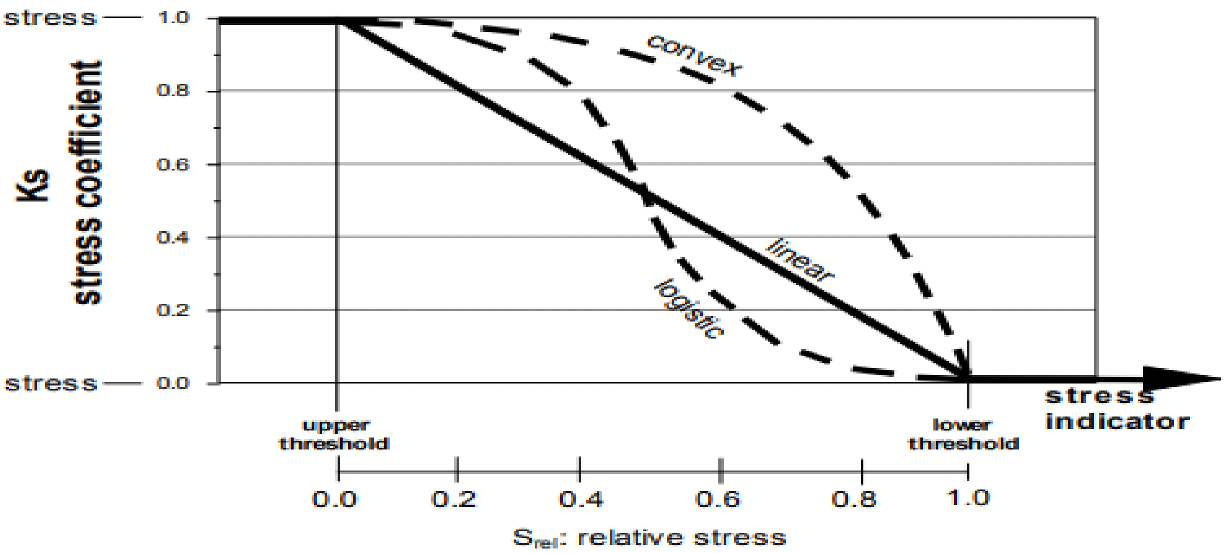

Figure 1: The stress coefficient (Ks) for various degrees of stress and for different shapes of the Ks curve (adapted from FAO Aquacrop training manual).

Therefore, water stress can hamper leaf expansion and trigger early senescence. This is described by use of water stress coefficient (Table 1). The water stress coefficient for canopy leaf expansion modifies the canopy growth coefficient. As long as water content is above the upper threshold, there is no water stress and Ks (stress coefficient) is 1. When water drops below that threshold, there is a reduction in leaf expansion growth, Ks is less than 1 and finally becomes zero at the lower threshold and there is no longer leaf expansion [32]. Another stress coefficient (Ks) takes into consideration of early canopy decline. As long as water is above that threshold Ks senescence is 1, canopy decline coefficient is zero and there is no early canopy decline. When water falls below the upper threshold, early canopy decline is triggered and the plant starts to lose leaves. By considering stresses for each day, Aquacrop simulates the actual canopy development. The same is true for root development where other stresses determine the actual root development [32]. Note that the thresholds for leaf expansion, senescence and Ks-curves are conservative crop parameters and the user should not adjust them.

Soil fertility stress has four effects on crop development; less dense canopy, slow in canopy development and decline in canopy cover and decrease in water productivity during the crop cycle. The smaller canopy cover will result into lower transpiration and consequently lower biomass [32]. This will also translate into a decline in water productivity. Therefore, a reduction in canopy cover and reduction in biomass water productivity will greatly result to a huge reduction in biomass and yields due to soil fertility stress. Soil fertility stress is henceforth described by using four stress coefficients. The stress coefficient for canopy expansion, stress coefficient for maximum canopy cover, canopy cover decline coefficient and stress coefficient for biomass water productivity [32].

Table 1: Considered soil water stress coefficients and their effect on crop growth (Adapted from FAO Aquacrop training manual).

Soil water stress coefficient	*Direct effect*	*Target model parameter*
Ks_{ear} *Soil water stress coefficient for water logging (aeration stress)*	*Reduces crop transpiration*	*Tr_x*
$Ks_{exp.w}$ *Soil water stress coefficient for canopy expansion*	*Reduces canopy expansion and (depending on the time and strength of stress) might have positive effect on Harvest index*	*CGC and HI*
$Ks_{pol.w}$ *Soil water stress coefficient for pollination*	*Reduces pollination and (depending on the time and strength of stress) might have a negative effect on Harvest index*	*HI_0*
Ks_{sen} *Soil water stress coefficient for canopy senescence*	*Reduces green canopy cover*	*CC*
Ks_{stom} *Soil water stress coefficient for stomatal closure*	*Reduces crop transpiration, root expansion and (depending on the time and strength of stress) might have a negative effect on Harvest index*	*$Tr_{x,}$ dZ and HI*

2.3 Crop Transpiration

In Aquacrop, evapotranspiration is separated between crop transpiration (Tr) and soil transpiration (E). It is described by multiplying the reference evapotranspiration with the coefficient for crop transpiration ($Kc_{tr)}$ to obtain crop transpiration and a coefficient for soil water evaporation (Ke) to derive soil evaporation [21]. Soil evaporation represents the non-consumptive use of water. The coefficient for soil water evaporation is proportional to the uncovered part of the soil, i.e. Ke-(1-CC). Crop transpiration essentially entails water removal from the surface of leaves to the atmosphere and is directly proportional to canopy cover. To simulate crop transpiration, Aquacrop uses the k_cET_o method. Where $K_{ctr,}$ is the crop coefficient, that is unique for each crop. ETO is the reference evapotranspiration, which expresses evaporative power of atmosphere and is dictated by weather conditions. Thus crop transpiration:

$$T_r = Kc_{tr} \times ETo. \quad (4)$$

The crop transpiration coefficient characterizes each crop, and expresses how the crop transpiration differs from the reference grass crop. Generally, when green canopy is large, crop transpiration coefficient is high which translates to high crop transpiration. When water in the root zone falls below the lower threshold there is stomata closure. That is simulated with the help of a water stress coefficient for stomata closure. Below the upper threshold line, the water stress coefficient for stomata closure becomes less than 1 and crop transpiration is limited. When water level reaches at permanent wilting point, water stress coefficient for stomata is zero and transpiration stops altogether. So by describing crop canopy development it is possible to obtain canopy cover (CC). Canopy cover is adjusted for micro-advective effects (*), hence canopy cover becomes CC*. Crop transpiration is simulated based on this equation:

$$Tr= K_{Ssto}*K_{ctr}*CC_{adj}*ET_{0.} \quad (5)$$

Where; ET_o is the evaporative demand of the atmosphere. Transpiration is proportional to canopy cover. The proportional factor is a crop specific i.e. it is a conservative crop parameter and during the duration of crop development, it is adjusted for aging and it collapses at senescence. When stresses affect transpiration, a Ks factor is introduced. There is a Ks $(_{aer})$ factor for water logging; for stomata closure $Ks_{(stom)}$, and for soil salinity, $Ks_{(salt)}$.

2.4 Biomass Production

Plants take in water through the roots that is subsequently transported via the xylem vessels to the leaves where substantial amount of it is lost by transpiration. 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 in. The process of photosynthesis converts carbon dioxide into carbohydrates, which are the building block for biomass. Thus, biomass produced is proportional to the amount of cumulative transpiration. That relationship is at the core for Aquacrop model. The biomass water productivity corresponds with the slope of the line. Biomass is consequently calculated by multiplying cumulative transpiration with the biomass water productivity: B = WP x cumulative (Tr). Biomass water productivity expresses the amount of biomass produced per water in m^2 of water transpired. However, biomass water productivity is only valid for specific climatic conditions and carbon dioxide concentrations.

To make biomass water productivity applicable in diverse climatic conditions, seasons and varied carbon dioxide concentrations, it is normalized by dividing cumulative transpiration with reference evapotranspiration. So, WP becomes WP* and henceforth biomass is plotted against cumulative transpiration divided by the daily reference evapotranspiration (ETo). The slope of the line now represents the normalized water productivity [21]. It is valid to reference carbon dioxide concentration of the year 2000, which was 369.41 ppm. Consequently, given the amount of water transpired, it is possible to calculate biomass based on the normalized water productivity of that crop.

2.5 Crop Yields

Crop yields are ultimately simulated by use of a harvest index, which is a fraction of the biomass that is the harvestable product. Harvest index is a conservative plant parameter but may vary from its reference value depending on timing, and extent of water and heat stresses [32].

2.6 Simulating the Effects of Climate Change on Crop Production

Aquacrop also simulates the effect of climate change on crop production. The expected changes due to climate change include an annual increase in carbon-dioxide concentration at the rate of 2 ppm per year in the next ten years which may get to 920 ppm by the year

2100 [32]. Increased air temperatures, reference evapotranspiration and altered rainfall patterns. Elevated carbon dioxide concentration will have an effect on crop transpiration and biomass water productivity. The first effect of increased carbon dioxide on crop development is on transpiration.

Due to high carbon dioxide concentration, a partial closure of stomata is observed which decreases transpiration [32]. However, the decrease in transpiration is negated by an increase in canopy temperature due to closure of stomata, which means low transpiration and hence a high temperature around the leaves, a lower relative humidity and as such a high transpiration [32]. Thus, due to high carbon dioxide concentration, we might have bigger leaves with more stomata. As such, the slight reduction in transpiration due to partial closure of stomata is partly undone by an increase in leaf area and canopy temperature that will result to only a small reduction in crop transpiration. However, increased carbon dioxide concentration has strong effect on biomass water productivity. Those effects are simulated in Aquacrop in form of a slight reduction in crop transpiration and a huge increase in water productivity leading to an overall positive effect on biomass production. When the carbon dioxide concentrations reach 500 ppm, the adjusted water productivity will be about 45% more. However, from face experiments that increase was found to be only 25% due to restrictions in the experiment such as the amount of nitrogen and other effects [32]. In Aquacrop by default, the increase of biomass water productivity is taken to be 35% after assuming sink strength of 50%, which the user can adjust depending on the type of crop. Conversely, Aquacrop also simulates the effects of increased air temperatures, reference evapotranspiration and altered rainfall patterns which in most situations are negative due to water stress. Water stress affects canopy development, the closing of stomata and alters the harvest index. Aquacrop simulates the combined effect.

2.7 Representative Concentration Pathways (RCP) and Global Circulation Models

Representative Concentration Pathways (RCP) are four greenhouse concentration trajectories adopted by the IPCC for its fifth assessment report (AR5) in 2014, which supersedes the Special Report on Emission Scenarios projections published in 2000. The pathways are used for climate modelling and research to describe four possible climate futures depending on how much greenhouse gases are emitted in the years to come, coupled by corresponding radiative forcing [33]. Radiative forcing is the difference in the energy balance that enters the atmosphere and the amount that is returned to space compared to the pre-industrial situation.

The four representative concentration pathways (RCP); RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 are named after a possible range of radiative forcing values in the year 2100 relative to preindustrial values (+2.6, +4.5, +6.0 and +8.5 w/m2 respectively [33]. The forcing causes changes to the Earth Climate system, altering Earth's radiative equilibrium, making temperatures to rise or fall. Positive radiative forcing implies the Earth receives more incoming energy from sunlight than it radiates to space. The net gain of energy causes warming. Conversely, a negative radiative forcing means the Earth losing more energy to space than it receives from the sun which produces cooling [33]. A different climate-modelling group, meaning that each has its unique characteristic that is not comparable to any other, developed each representative concentration pathway. Representative

Concentration Pathways are different from previous scenarios in that, first; there are no fixed sets of assumptions related to population growth, economic development or technology associated with any RCP. Meaning that, there are many social-economic plausible futures that lead to the same level of radiative forcing. By that, researchers are able to test various permutations of climate policies and social, technology and economic circumstances. Secondly, Representative Concentration Pathways are spatially explicit providing information a global grid at a resolution of approximately 60 kilometres. That gives the spatial and temporal information about the location of various emissions and land use changes. An important improvement since the location of some emissions affects their warming potential. The four representative concentration pathways are consistent with certain socio-economic assumptions, though to be replaced later by 'Shared Social-Economic Pathway' that will provide flexible descriptions of possible futures within each representative concentration pathway. The RCP includes:

[1]. RCP 8.5 - High emissions. Represents a future with no policy changes to reduce emissions. The International Institute developed it for Applied System Analysis in Austria. According to this RCP, the future will be characterized with; Three times today's C02 emissions by the year 2100; rapid increase in methane emissions; increase use of cropland and grassland driven by an increase in population; A world population of 12 billion by 2100; lower rate of technology development; heavy reliance on fossil fuels; high energy intensity and; no implementation of climate policies.

[2]. RCP 6.0. Intermediate emissions. The National Institute developed it for Environmental Studies in Japan. According to this RCP, the future is characterized by: High reliance on fossil fuel; Intermediate energy intensity; Increasing use of cropland and declining use of grasslands; Stable methane emissions and; Carbon dioxide emissions attaining peak levels by the year 2060 at 75% above today's levels then declining to 25% per above the current rate.

[3]. RCP 4.5. Intermediate emissions. This was developed by the Pacific Northwest National laboratory in the United States of America. Anticipates a radiative forcing stabilizing shortly after the year 2100. According to this RCP, the future is consistent with; Lower energy intensity; Strong reforestation programs; Decreasing use of cropland and grassland due to yield increases and dietary changes; Stringent climate policies; Stable methane emissions and; Carbon dioxide emissions increasing slightly before beginning to decline around the year 2040.

[4]. RCP 2.6. Low emissions. It was developed by PBL. Netherlands Environmental Assessment Agency. Anticipates radiative forcing to reach 3.1W/m^2 before returning to 2.6W/m2 by the year 2100. To achieve reduced radiative forcing levels a huge reduction in greenhouse gas emissions is required. The future would necessarily require; Declining use of oil; Low energy intensity; A world population of 9 billion by the year 2100; increase in use of cropland due to bio-energy production; Intensive animal husbandry; Reduction of methane emissions by 40%; Carbon dioxide emissions to stay at today's level up to 2020; decline and become negative by the 2100 and; Carbon dioxide emissions to peak at the year 2050, followed by a modest decline to around 400 ppm by the year 2100.

Therefore, to simulate crop yields first to select one of the emissions scenario or representative concentration pathways as the carbon dioxide file. Several options are available, the scenarios and pathways differ because they represent different storylines. They differ in their assumption for population and economic growth, introduction of more efficient technologies. 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 [32].

Lack of consensus at the global level on how to effectively tackle climate change, coupled with the understanding that no single mitigation measure can effectively sequester the amount of greenhouse gases already present in the atmosphere, necessitate a shift of focus to adaptation, especially for the most vulnerable farming communities like those in Sub Saharan Africa. The reliance of their livelihood and national economies on climate sensitive parameters such as rainfall and temperature, coupled with endemic poverty puts them into a precarious position in regard to exposure to extreme climatic events that exacerbate their food insecurity situations. Observation 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. That, coupled with archaic farming practices greatly undermined the ability of the smallholder farmers to grow adequate crop yields to meet family food requirements and have surplus for sale. It is in this regard that this study sought to investigate how Aquacrop model would help inform climate smart agriculture based on two interventions; double digging and making of Zai pits on which varying levels of farmyard manure was incorporated.

3. Materials and Methods

3.1 Description of Study Site

This study was conducted at Wiyumiririe location, situated in Ngobit ward of Laikipia County. The site is located about 80km South-west of Nanyuki (S 00°04.766: E 036°39.174) and 7212 feet above the sea level (Figure 2). Wiyumiririe location falls under the Arid and Semi-Arid Lands of Kenya (ASAL) characterized by low and erratic rainfall, high day temperatures and low night temperatures. The black cotton soils predominant at Wiyumiririe are generally fertile. However, the inadequacy and erratic nature of rains were factors that limited cultivation of crops. Due to that, farmers had a challenge determining the correct time for planting. In most situations' crops dried up in the field before reaching physiological maturity. In other situations, crops were affected by frost bite more so in the months of January. Moreover, farmers were observed to practice rudimentary methods of farming. Apart from mild usage of farm yard manure, there were no efforts to use hybrid seeds or follow well defined agronomic practices. 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. Additionally, 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. For those reasons this study purposed to investigate how two Climate-Smart Agriculture options (Double digging and Zai pits) together with Aquacrop model could help the community improve sorghum crop yields as a gateway to alleviating their food security concerns and eventually build resilience to climate change.

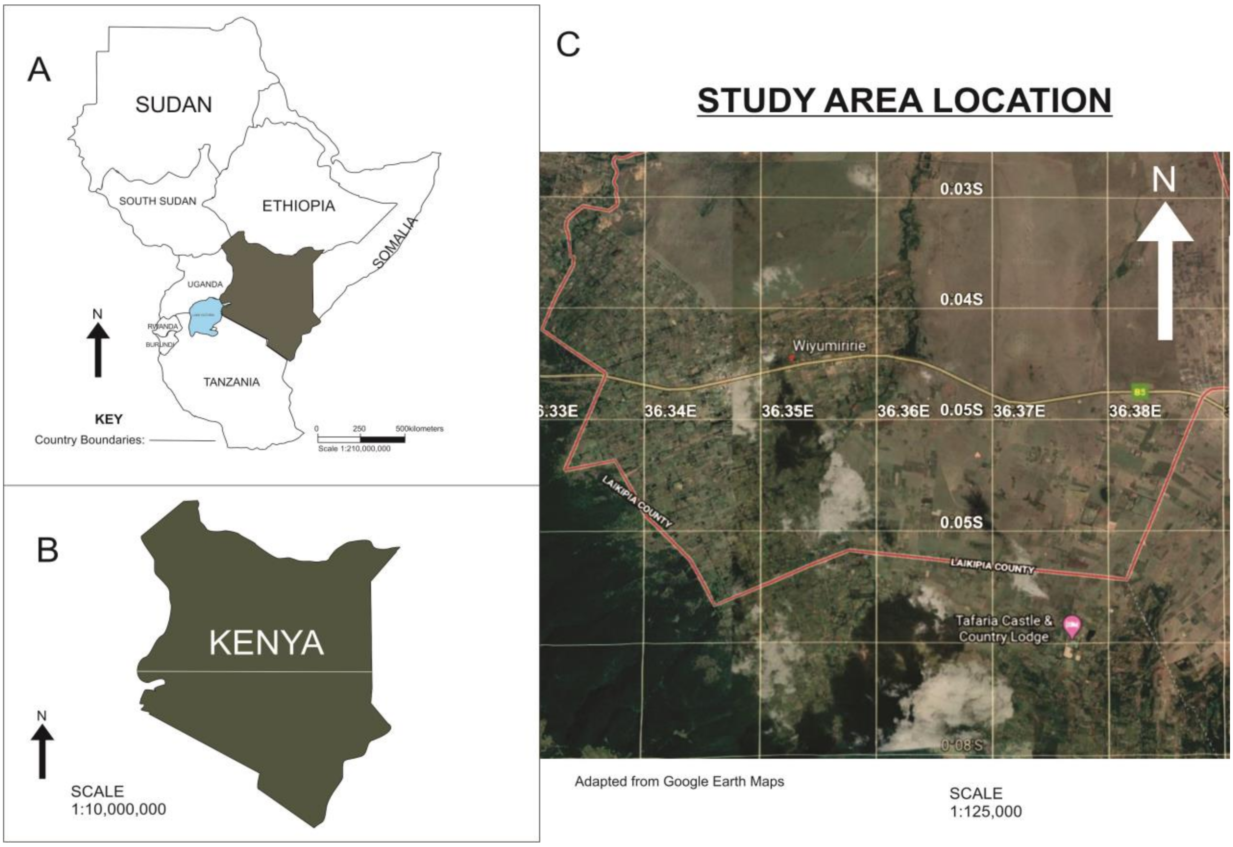

Figure 2: Wiyumiririe location in Laikipia County, Kenya.

3.2 Field Layout and Experimental Design

The field trial was carried study on a 100 ft by 100 ft piece of land 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 database, calibration for this study entailed describing the environment and making adjustments to non-conservative crop parameters. The experimental plot was set up in a split-plot design (Table 2) where double digging, Zai pits and conventional farming (taken as control) were the main factors whereas the varying levels of farmyard manure was the minor factor. The site was cleared of vegetation and subdivided into three equal portions. On one section, double digging, the second portion by constructing Zai pits, did land preparation 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 8 m long and 0.6 m wide. In double digging, individual portions were further subdivided into four equal parts labelled 1 to 4. Portion 1 was dug to 30 cm deep and soil piled adjacent to it. Then by use of a pitchfork the remaining subsoil was loosened another 30 cm deep. Portion 2 was dug next, back filling the previously dug portion one but after mixing soil 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 mixed with farmyard manure and used to fill up portion 4. There were four levels of farmyard manure applied (5 tons/ha, 3.75 tons/ha, 2.5 tons/ha and 1.25 tons/ha) and the unfertilized control (With no manure application) which together constituted the five treatments.

Table 2: 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	¼	1	3\4	0	1/2

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

On the portion reserved for construction of Zai pits, pits were demarcated and dug. Each pit measured 60 cm by 60 cm wide and 60 cm deep. The distance from one pit to the other within the row and between rows was 60 cm. 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 20 kg 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, 60 cm deep. In the portion where double digging was carried out, a 2 kg container was used to measure manure. To do that, planting holes (60 cm 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 in double both digging and Zai pits. In subsequent planting seasons the amounts of farmyard manure applied was adjusted to cater for residual effect.

3.3 Aquacrop Model Calibration

3.3.1 Calibration

The calibration and validation process was ran 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 [34]. Acceptable pattern of parameters was 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. 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.

3.3.2 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), Et_o 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 (Lamuria weather station) were used to calculate daily reference evaporation using the built-in ET_o calculator.

3.3.3 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 (K_{sat}). To achieve that, representative samples from each treatment were taken to Kenya Agricultural and Livestock Research 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 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 15 cm and analysed 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.

$$(M_{S+W}) = \text{Solid and water. } (6)$$

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^{0}c 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.

$$\theta_m = \frac{m_{s+w} - m_s}{m_s} = \frac{m_w}{m_s}. \ (7)$$

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.

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

Where: θ - volumetric water content; θ_m - mass percentage of water; ρ_b - bulk density of soil; ρ_w - bulk density of soil.

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

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 millimetres 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 (0.60 m). The values obtained were entered in the Aquacrop software as field data.

Results for soil water content measured from the field at two week intervals 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 60 cm, 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 30 cm and 4 m deep) was dug between the main plots and measurements done at regular intervals.

3.3.4 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 for all treatments. Calibration for soil fertility entailed making qualitative assessment of the canopy development then assigning values through trial and error as suggested by developers of the model [34]. 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 40 cm by 30 cm giving an approximately plant density of 83,333 plants/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 as to attain the correct plant population. The size of the germinating sorghum seedling is a conservative crop parameter and the same value (5 cm^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 week intervals 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 I pad. 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 analysed 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. 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°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 average yields were divided by biomass at harvest time.

3.3.5 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.

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

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

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

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.

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.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - O)(S_i - S)}{\sqrt{\sum_{i=1}^{n}(O_i - O)^2}\sqrt{\sum_{i=1}^{n}(S_i - S)^2}} \right)^2 . (12)$$

Five: The Willmontt's 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.

$$d = 1 - \frac{\sum_{i=0}^{n} (Pi - Oi)^2}{\sum_{i=0}^{n} \{Pi - \mu oi\} + \{Oi - \mu Oi\}^2} . (13)$$

3.3.6 Simulation for Current and Future Weather Conditions

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 and an average of 17 global circulation models derived from MarkSim weather generator; the web version for IPCC AR5 data (CMIP5). The GCM models run were; BCC-CSM1-1, BCC-CSM1-1-M, CSIRO-Mk3-6-0, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M GISS-E2-H GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MRI-CGCM3 and NorESM1-M. Previous studies [35 and 36] 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

4. Results and Discussion

4.1 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. 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 3.

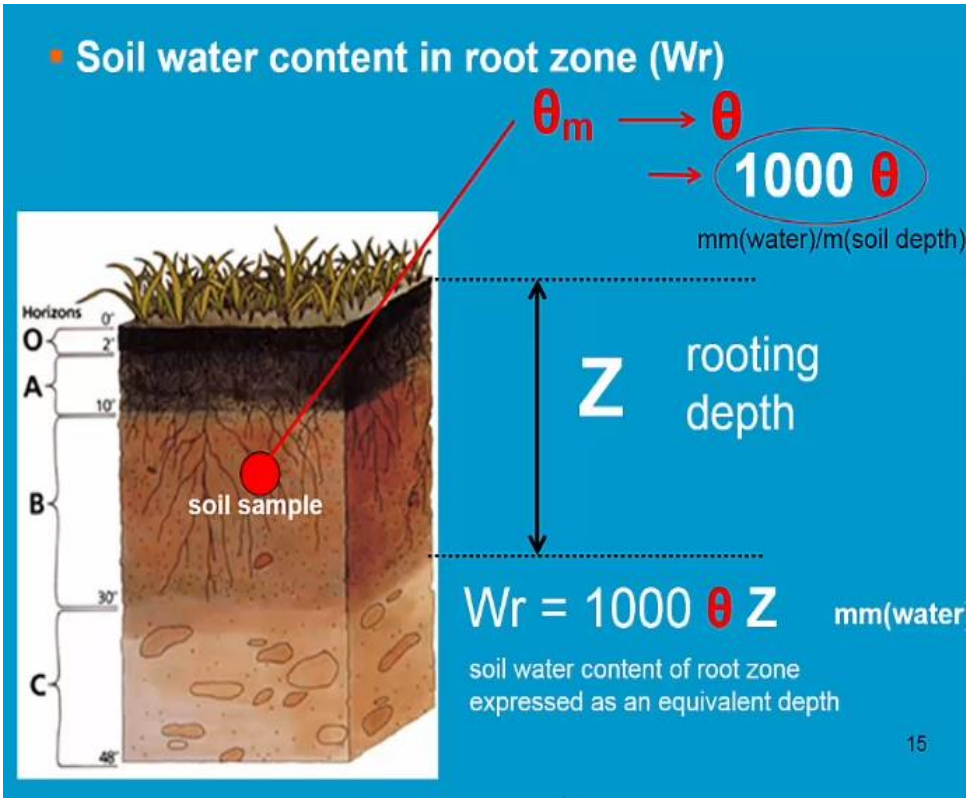

Figure 3: Determination of soil water content at the root zone (Adapted from Aquacrop training module 2017), Where; Wr is the soil water content at the root zone, θ is the volumetric content at the root zone, and Z is the effective rooting depth.

Table 3: 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 1150 m and 1750 m above sea level. The study area receives 250 mm to 500 mm 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. Figure 4 shows the model output for mean monthly rainfall during the study period.

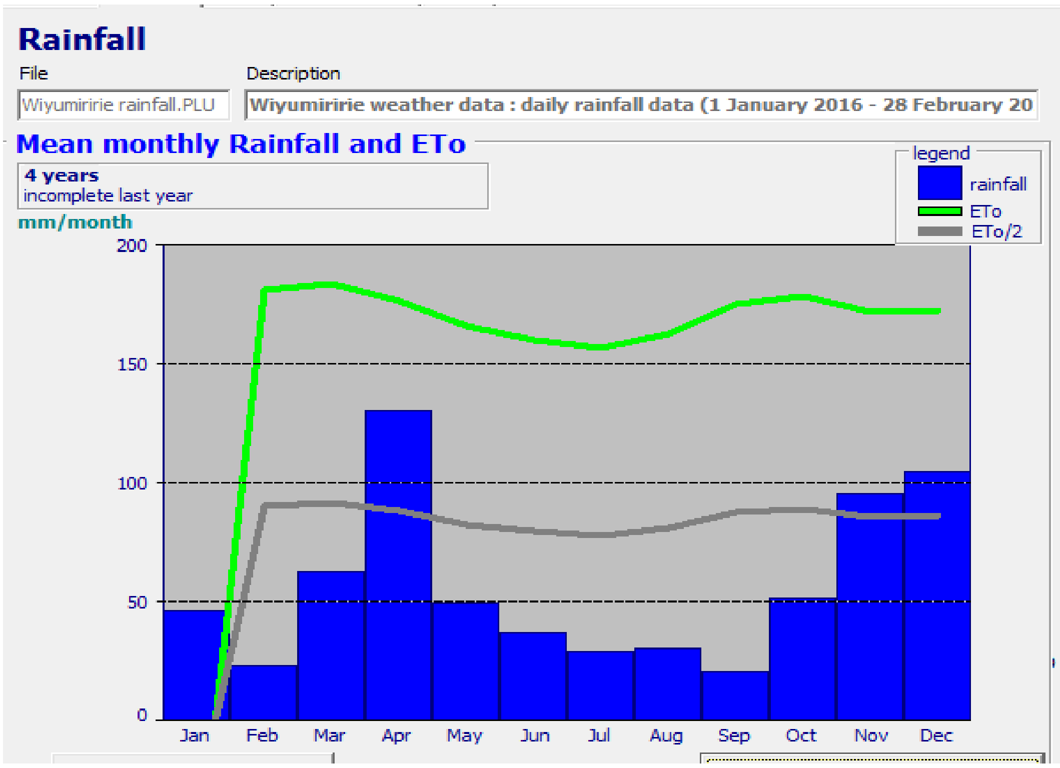

Figure 4: Mean monthly rainfall from January 2016 to February 2019.

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 – 120 days. In spite of that, the ability of double digging and Zai pits 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. The 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.

In Kenya, Sorghum grows well within the temperature range of 15 °C and 35 °C. However, in this study the base and upper temperatures (10 °C and 30 °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 [37] 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 [37]. 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 5 shows the model output for mean maximum and minimum air temperatures during the study.

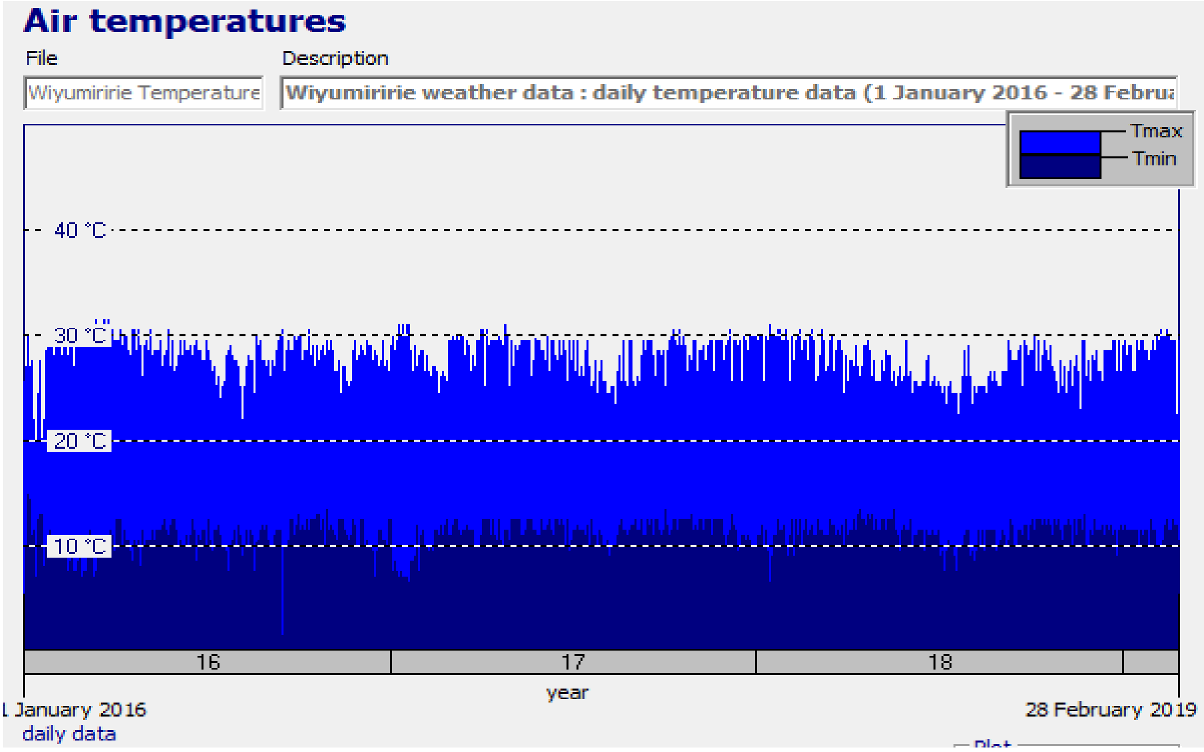

Figure 5: Daily minimum and maximum air temperatures from January 2016 to February 2019.

4.2 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 2 tons/acre of farmyard manure or compost that was done as part of this study. Later analysed 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 4 shows the initial nutrient status of the soil.

Table 5 shows the soil profile characteristics at the beginning of the growing cycle that formed the input data to the model. Initial soil conditions showed that the treatment for double digging and manure rates of 5 tons/ha had the highest amount of total available water (TAW = 173 mm) while conventional farming had the least (TAW = 75 mm). 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 5 tons/ha, the water level remained above the threshold for early canopy senescence during the entire cropping season, a situation that was not found under conventional farming.

Table 4: 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

Table 5: Soil profile characteristics at the beginning of the cropping season.

Treatment	TAW	PWP	FC	SAT	Ksat
DDFR	173	16.4	33.7	45.4	828.0
DD¾R	144	19.1	33.5	43.1	160.8
DD½R	147	18.5	33.2	42.5	1248.0
DD¼R	160	16.4	32.4	42.4	768.0
DDCONT	156	19.0	34.6	39.4	9.6
ZPFR	162	18.2	34.4	46.2	1752.0
ZP¾R	160	17.1	33.1	44.1	1562.0
ZP½R	172	18.2	35.4	44.0	3096.0
ZP½R	163	16.5	32.8	43.5	1872.0
ZPCONT	167	17.5	34.2	42.5	2.4
CONVF	75	24.6	32.3	40.6	125.0

Figure 6 shows the model output for soil-water retention at the root zone for Zai pit treatment with incorporated farmyard manure at the rates of 5 tons/ha. Across the board, it was evident that the prioritized interventions were effective in improving soil water content. 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 soil water content in most of the treatments. 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, [38,39].

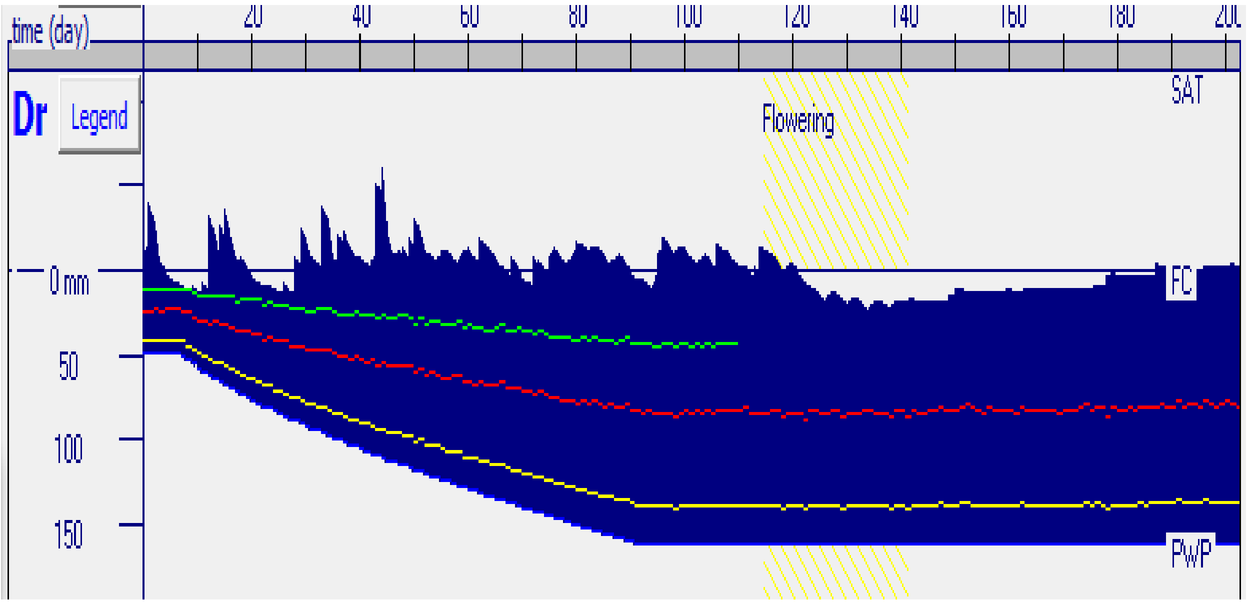

Figure 6: Soil water retention at the root zone during the crop cycle for Zai pit intervention, validation trial. The figure shows water retention and movement in the root zone indicated by the blue colour. The upper blue line (0 mm) is the level at which water was at field capacity and the lowest point was a permanent wilting point (150 mm). 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.

4.3 Crop Parameters

Calibration for double digging and Zai pits interventions was feasible for all levels of farmyard manure, unfertilized control and in all seasons. However, calibration for conventional farming where farmyard was incorporated at the rates of 3.75 tons/ha or lower wasn't possible for inadequate canopy cover. Compared to the reference crop, the simulated effect of soil fertility varied considerably. The effects were in form of reduction in maximum canopy cover, canopy growth coefficient, canopy cover decline per day and biomass water productivity (Table 6). 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 3.75 tons/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.

At half the recommended rates of farmyard manure the study observed 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.

Table 6: Calibration for soil fertility.

Treatment	**Soil fertility stress**	**Effect (reduction)**			
		CCx	**CGC**	**CC%/day**	**WP***
DDFR	16	1%	1%	0%	32%
DD¾R	19	1%	3%	0.00	19%
DD½R	20	0	1%	0.01%	41%
DD¼R	30	3%	2%	0.00%	51%
DDCONT	45	55%	33%	0.15%	40%
ZPFR	16	3%	1%	0.25%	15%
ZP¾R	19	6%	4%	0.01%	30%
ZP½R	20	10%	6%	0.02%	29%
ZP¼R	30	20%	1%	0.02%	33%
ZPCONT	45	31%	7%	0.02%	54%
CONVF	45	49%	35%	0.25	63%

Where; CCx is the maximum canopy cover; CGC is canopy growth coefficient and WP is biomass water productivity normalized for the environment. DDFR- double digging at full rates of farm yard manure, DD¾R, is double digging treatment and three quarter rates of farm yard manure; DD½R is double digging and half rates of farmyard manure; DD¼R is double digging and quarter rates of farm yard manure; DDCONT is double digging with no manure application ZPFR- Zai pit at full rates of farm yard manure, ZP¾R, is Zai pit treatment and three quarter rates of farm yard manure; ZP½R is Zai pit and half rates of farmyard manure; ZP¼R is Zai pit and quarter rates of farm yard manure; ZPCONT is Zai with no manure application and CONV is conventional farming*

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 [34], there may be need to carry out a more accurate calibration process based on actual in-season soil nutrient analysis.

4.4 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 (1.70 gms/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 [42]. Table 7 shows the validated field data for the long growing season.

Table 7: Field data used for validation.

Treatment	29 days		141days		Harvest
	CC [%]	B[t/ha]	CC [%]	B[t/ha]	Biomass[t/ha]
DDFR	8.8	0.190	83.0	10.030	18.122
DD¾R	8.6	0.051	76.0	13.32	16.789
DD½R	8.4	0.048	75.0	9.317	13.157
DD¼R	6.4	0.043	72.8	8.342	11.569
DDCONT	2.2	0.040	28.8	4.293	5.672
ZPFR	7.6	0.050	79.4	12.123	15.982
ZP¾R	6.4	0.049	74.8	9.916	14.986
ZP½R	5.6	0.043	72.0	10.761	13.056
ZP¼R	5.5	0.041	61.8	8.916	11.284
ZPCONV	2.1	0.031	25.0	4.528	4.994
CONV	0.1	0.012	7.9	1.472	1.641

4.5 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 5 tons/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 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 stomata. 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 5 tons/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% 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 21temperature 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 [40], [41], and [42]. However, these results require to be taken with caution because the impacts of elevated temperatures on crop physiology, soil chemical properties and pests and diseases is not yet determined.

4.6 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. 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 8: Results for evaluation of simulated data.

Treatment	Statistical index	Canopy cover [%]	Biomass [t/ha]	Soil water content [mm]
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%	10.887	162.9
	Average SM	48.9%	10.635	158.3
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%	9.942	143.6
	Average SM	43.4%	10.085	144.8
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%	7.831	131.2
	Average SM	41.5%	8.037	131.7
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%	6.623	123.3
	Average SM	40.2%	7.147	131.9

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%	3.416	123.2
	Average SM	14.4%	3.334	129.8
ZAIPTFR	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	9.176	201.5
	Average SM	40.5	8.873	195.1
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%	8.426	189.2
	Average SM	40.1%	8.225	184.5
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%	7.974	140.3
	Average SM	37.7%	7.890	134.7
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%	6.774	133.0
	Average SM	32.4%	6.591	122.9
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%	3.280	113.1
	Average SM	11.8%	2.825	110.8
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%	1.338	142.5
	Average SM	7.6%	1.322	162.1

4.7 Scenarios for Policy Makers

This study investigated how Aquacrop model 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 9.126 tons/ha which is more than double the average production in Kenya of 4 tons/ha and has the potential to go up to 10.86 tons/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 6.852 tons/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 5tons/ha is 8.342 tons/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 2.792 tons/ha and Zai pits 2.316 tons/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 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.

5. Conclusions

This article demonstrated that double digging, Zai pits and Aquacrop model were effective methods in understanding the effects of climate change and variability on sorghum yields sufficient to inform policy makers. Double digging and Zai pits were effective rainwater-harvesting technologies that enabled crops cultivated under those regimes to grow and attain maturity with minimal stress. On the other hand, Aquacrop was effective in simulating canopy cover, biomass and yields, results that were consistent with field observations. Moreover, the model managed to demonstrate the effects of climate change on sorghum yields, which were useful in developing scenarios for policy makers. Therefore, if the interventions explored in this study are embraced as part of Climate-Smart Agriculture approach, they provide a plausible option for communities in similar environment conditions worldwide to become food secure and resilient to Climate change

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