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ASSESSMENT OF YIELD RESPONSE TO WATER FOR DRY BEANS (*PHASEOLUS VULGARIS L.*) USING AQUACROP MODEL UNDER CHANGING CLIMATE; THE CASE OF EMBU, KENYA

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Assessment of Yield Response to Water for Dry Beans (*Phaseolus Vulgaris L.*) By Simulation Using Aquacrop Model under Changing Climate; The Case of Embu, Kenya

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DECLARATION

This research is my original work and has not been presented for award of a degree in any other University.

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DEDICATION

This work is dedicated to my dear parents Mr. and Mrs. Gichovi who have been instrumental in my Education**.**

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ABBREVIATIONS AND ACRONYMS

AER	Agro Ecological Zone
AFC	Agricultural Finance Corporation
AIDS	Acquired Immune Deficiency Syndrome
ASDSP	Agricultural Sector Development Support Program
ASL	Above Sea Level
CA	Conservation Agriculture
CIAT	International Centre for Tropical Agriculture
CIDP	County Integrated Development Plan
CO_2	Carbon (iv) Oxide
CC	Canopy Cover
CSA:	Climate Smart Agriculture Practices
EU	European Union
FAO	Food and Agriculture Organisation
KALRO	Kenya Agriculture and Livestock Research Organisation
KNBS	Kenya National Bureau of Statistics
GHG	Green House Gases
HIV	Human Immune Virus
IFAD	International Fund for Agricultural Development
IPCC-	Intergovernmental Panel on Climate Change
MoALF	Ministry of Agriculture and Livestock
PVC	Polyvinyl Chloride
UN	United Nations
SDG	Sustainable Development Goal
UNICEF	United Nations International Children's Emergency Fund
WFP	World Food Programme
WHO	World Health Organisation
CGoE	County Government of Embu

ABSTRACT

Globally countries have been on the struggle to get industrialized, trading in their regional setups and internationally. This in return has led to increase in the release of high quantities of greenhouse gases into the atmosphere. The gases have caused the greenhouse effect on the planet leading to a rise in terrestrial temperatures. this rise has led to changes in the patterns of weather and climate globally. These changes in the world climatic patterns has contributed to unreliability of the production systems that rely on rainfall. The worst hit is the agriculture sector and the small scale farmers across the globe have borne the blunt of climate change being worst hit. Flooded waters due to high intensity precipitations over short durations of time wash away livestock and crops as they make their way to the already rising seas. The small scale farmer who relies on simple production systems for subsistence purposes has globally been hit by food insecurity. Drought incidences have also been on the rise globally thereby increasing the cases of starved and malnourished people especially women and children. This study sought to respond to the climate change related problems affecting small scale farmers who usually produce to feed their families and sell the surplus. In that regard the study used Food and Agriculture Organization (FAO)'s AquaCrop model to assess the yield response to water for dry beans while focusing on a small village in the rural Eastern Kenya. (Embu). It involved planting of a crop in the month of April 2018 that would provide the necessary crop phenology data and the environment data for the site it was cultivated. This data would later be fed in to the model in fine tuning process. Through calibration the model was finally customized for running simulations for the local conditions. The model accurately predicted the expected yield under climate change scenario in the next ten years. If farmers in the area continue to practice conventional farming methods, then there shall be a 10% reduction in the level of yield in a span of ten years to come. Another treatment; conservation Agriculture that involves placing of organic mulch to cover the soil indicated an 8% increase in yields in the same span of time. The model was accurate in predicting future yields among other parameters. It was instrumental in giving various yield gaps between different combination of management practices on the field. The study recommended the model for use by researchers, policy makers, agriculture extension staff in evaluating several scenarios within a short time giving accurate and practical recommendations.

CHAPTER ONE: INTRODUCTION

1.1 Background Information

The United Nations sustainable development goal two focuses on ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture. In its 2017 progress report, the UN states that efforts to combat hunger and malnutrition have advanced significantly since 2000. However, ending hunger, food insecurity and malnutrition for all will require continued and focused efforts, especially in Asia and Africa.

More investments in agriculture, including government spending and aid, are needed to increase capacity for agricultural productivity. Ending hunger demands sustainable food production systems and resilient agricultural practices. One aspect of that effort is maintaining the genetic diversity of plants and animals, which is crucial for agriculture and food production. In 2016, 4.7 million samples of seeds and other plant genetic material for food and agriculture were preserved in 602 gene banks throughout 82 countries and 14 regional and international centres (Nations, 2017). This was a 2% increase since 2014. Animal genetic material has been cryoconserved, but only for 15 per cent of national breed populations, according to information obtained from 128 countries (FAO, 2016). According to FAO (2016), the stored genetic material is sufficient to reconstitute only 7 per cent of national breed populations should they become extinct. As of February 2017, 20 per cent of local breeds were classified as at risk.

The share of sector-allocable aid allocated to agriculture from member countries of the Development Assistance Committee of the Organization for Economic Cooperation and Development (OECD) fell from nearly 20 per cent in the mid-1980s to 7 per cent in the late 1990s, where it remained through 2015 (Nations, 2017). The decline reflects a shift away from aid for financing infrastructure and production towards a greater focus on social sectors.

In 2016, 21 countries experienced high or moderately high domestic prices, relative to their historic levels, for one or more staple cereal food commodities. Thirteen of those countries were in sub-Saharan Africa. The main causes of high prices were declines in domestic output, currency depreciation and insecurity. Localized increases in fuel prices also drove food prices higher

Food and Agriculture organisation of the united nations (FAO, 2017)in one of its reports indicates that, after steadily declining for over a decade, global hunger appears to be on the rise, affecting

11%of the global population. This report further indicates that the estimated number of undernourished people increased from 777 million in 2015 to 815 million in 2016.

Famine struck in parts of South Sudan for several months in the year 2017 and food insecurity situations at risk of turning into famines were identified in other conflict-affected countries, namely Nigeria, Somalia and Yemen.

The food security situation visibly worsened in parts of sub-Saharan Africa, South Eastern and Western Asia. This was most notable in situations of conflict, in particular where the food security impacts of conflict were compounded by droughts of floods, linked in part to El Niño phenomenon and climate-related shocks. Over the past ten years, the number of violent conflicts around the world has increased significantly, in particular in countries already facing food insecurity, hitting rural communities the hardest and having a negative impact on food production and availability (FAO, 2017)

In the first quarter of 2017, 2.7 million people were classified as severely food insecure in Kenya. Up to three consecutive years of poor rains have led to diminished food production and exhausted people’s coping capacities particularly in the northeastern, eastern and coastal areas of Kenya. Additionally, chronic and intensifying conflicts in the region have generally driven up displacement. Food insecurity and malnutrition are highly prevalent in Kenya’s arid and semi-arid lands. Interventions targeting livestock dependent households have benefited livestock keepers in the counties of Turkana, Marsabit, Samburu, Isiolo, Kitui, Tana River and Garissa (FAO, 2017).

Semi-arid lands within Kenya’s Agricultural Climatic Zone 5 represent the country’s next agricultural frontier. A jointly developed program by the European Union (EU), IFAD and FAO, the Kenya Climate-Resilient Agricultural Livelihoods Programme has been set up to increase productivity and profitability of smallholder farmers by promoting and up-scaling good agricultural practices and conservation agriculture in the country’s productive semiarid areas. The focus is therefore on water harvesting and conservation, natural resource management and climate-smart agriculture as well as the involvement of the private sector and financial institutions. By bringing inputs and services closer to farmers, the project has succeeded in increasing marketing activities and private sector participation, with about 3 500 farmers currently engaged in contract farming for a value of Ksh 3 billion (FAO, 2017). This study sought to adress the issue of food insecurity by assessing the dry beans' yield response to water in a semi-arid environment and proposing posible coping mechanisms to drought and climate change.

1.2 Statement of the Problem

The Food and Agriculture Organisation of the United Nations records that there was a reduced cereals output obtained in 2017 in Kenya due to unfavourable weather conditions. However, there were notable reduction in prices of maize mostly due to sustained imports. This year (2018), Kenya recorded abundant rains in March and April that benefited the establishment and development of crops and improved pasture conditions. At the same time, there were widespread floods resulting in displacement of about 24, 000 individuals. As of January 2018 there were 2.35 million people who faced severe food insecurity, this was 30% less than in October 2017. Generally, in Kenya, there has been notable improvement in food security situation in 2018 (FAO, 2018).

The agriculture sector is the main stay of the Kenya's economy. It provides 26% of the GDP, and 80% of the rural population derives their livelihood from agriculture and other related activities according to Global Yield Gap Atlas, 2018. Agriculture is also the country's major earner of foreign exchange contributing about 60% of export earnings. Farms in Kenya range from small-scale subsistence family operations to large-scale mechanized enterprises with crops and/or livestock. Food crops and other annual crops are grown according to rainfall amounts and temporal distribution, which is bimodal in nature. The long rains occur from March to and including May, while the short rains occur from October to and including December. Following these rainfall patterns, annual single-crop systems and double-crop systems can be found (Adimo, n.d.). Farmers practice mainly rain-fed agriculture, and therefore, are vulnerable to climate change. Availability of weather information is essential for planning food production. In 2013, the GDP of Kenya was US$ 44 101 million with agriculture contributing 30 percent to the GDP. In Kenya, about 69 percent of the total economically active population is employed in agriculture. Agriculture accounts for 65 percent of Kenya's total exports and comprises five major sub-sectors: industrial crops, food crops, horticulture, livestock and fisheries. Industrial crops and horticulture are the two main agricultural exports. Agriculture in Kenya is mainly rain-fed. Irrigated agriculture accounts for only 2.4 percent of the cultivated area, but contributes 3 percent to the GDP and 18 percent to the national agricultural production. It employs about 3 million people: 900 000 directly and indirectly in public schemes, over 2 million in community-based schemes and around 82 500 in commercial farms. In the past, irrigation development not only aimed to secure and stabilize the food supply in face of droughts and to provide employment, but also to provide settlement for the landless when (re)distributing the equipped land (FAO, 2018).

There's therefore need to support rain-fed agriculture sector with technologies that ensure conservation of the soil moisture in the dry seasons and in cases of drought. This can be enhanced through climate smart agricultural systems and through increased research in the field of climate change adaptation technologies for the agriculture sector.

Climate-smart agriculture which is an approach for transforming and reorienting agricultural systems to support food security under the new realities of climate change. Widespread changes in rainfall and temperature patterns threaten agricultural production and increase the vulnerability of people dependent on agriculture for their livelihoods, which includes most of the world's poor. Climate change disrupts food markets, posing population-wide risks to food supply. Threats can be reduced by increasing the adaptive capacity of farmers as well as increasing resilience and resource use efficiency in agricultural production systems.

Climate smart agriculture promotes coordinated actions by farmers, researchers, private sector, civil society and policymakers towards climate-resilient pathways through four main action areas; building evidence, increasing local institutional effectiveness, fostering coherence between climate and agricultural policies and linking climate and agricultural financing. Climate smart agriculture differs from 'business-as-usual' approaches by emphasizing the capacity to implement flexible, context-specific solutions, supported by innovative policy and financing actions (Lipper et al., 2014).

1.3 Objectives

1.3.1 Main Objective

The main objective of this study was to assess the yield response to water for dry beans (KAT Bean1) using AquaCrop model.

1.3.2 Specific Objectives

The specific objectives of this study were to:

i. Calibrate AquaCrop model for running simulations on the yield response to water for dry beans
ii. Simulate the yield potential and response to water for dry beans (KAT Bean1) under changing environmental (climatic) conditions
iii. Conduct a yield-gap analysis for dry beans under different treatments (conventional farming and conservation agriculture) in the study area and propose policy recommendations for best site specific results.

1.4 Research Questions

i. Is the yield potential for dry beans dependant on the amount of water available during the growing season?
ii. Does climate change have any impact on the future yields of dry beans in the study area?
iii. Does the type of management practices and their combination affect the yield level in beans?

1.5 Justification of the study

Five of the UN's 17 SDGs are directly related to agriculture. Kenya's economy heavily relies on rain-fed agriculture. Only 20% of land in Kenya is arable with the rest being dominated by arid and semi-arid land that barely supports rain-fed agriculture. This small portion of land that produces food for the entire nation has not been spared by the adverse effects of climate change especially erratic rainfall. Majority of Kenya's rural households are comprised of subsistence farmers and rely on rain-fed agriculture for crop production to feed their families. They sell the surplus if any. However, that has barely been the case in the past decade due to unreliability of rainfall, increased temperatures and land degradation. There have been several cases of drought in the country and including in the study area. The food crops grown in the area include maize, beans and other cereals which have recorded low yields over the past few years. This has resulted to escalated poverty levels since the main sources of income for these families have been affected by the negative impacts of Climate Change. A number of groups are most vulnerable. These include;

the poor, women, people living with disabilities, people affected and infected with HIV& AIDS. These groups have the least ability to withstand climate shocks and their inability to access the main factors of production in terms of resources like land and capital. Therefore, there is great need to help the farmers to adequately adapt to the impacts of the changing climate. Consequently, food security will be enhanced. This study therefore assessed the yield response of beans to water and further evaluate the best management practices to realise optimum yields for the study area in a changing climate. The results contribute to a solution to the current challenge of erratic and unreliable rainfall in the area. The study further recommends the best policies for the crop growing in the region and this may bring about a sustainable solution.

1.6 Scope and limitations of the Study

This study was to be carried out at the Kenya Agricultural and Livestock Research Organisation (KALRO) Embu Kenya station's research plots upon a successful agreement on a request that had been made by paying a courtesy call at the centre's offices in March 2018. The research centre is located in the area of study i.e. Embu County and the crop of beans is grown by over 95% of farmers in the region according to a report of 2014 from the station, despite crop failure in the recent years. Having the research crop grown at the station would ensure effective data collection during the growing season and being within a research centre this would ensure maximum controls and any external forces would be put to check, secondly the meteorological weather station is just adjacent to the KALRO station and this study relied on rainfall, Temperature, wind, humidity and CO_2 data. However, the officer in charge of conservation agriculture which the study broadly encompassed advised that for best results this needed to be done at a different location and this would necessitate leasing some piece of land. He also argued that the bureaucracy in acquiring plots at the research centre would take much longer and thus affect the study bearing in mind that there was a limitation of time. The major limitation to this study was time and therefore, the data collection was only conducted for one growing season (April to June 2018). This then means that the crop that was grown took approximately two months to reach maturity. This further dictated the choice of crop to a dry land variety that takes a maximum of 70 days to maturity.

CHAPTER TWO: LITERATURE REVIEW

2.1 Climate Change and Climate Change Adaptation

Climate change threatens our ability to ensure global food security, eradicate poverty and achieve sustainable development. Greenhouse gas (GHG) emissions from human activity and livestock are significant drivers of climate change, trapping heat in the earth's atmosphere and triggering global warming. Climate change has both direct and indirect effects on agricultural productivity including changing rainfall patterns, drought, flooding and the geographical redistribution of pests and diseases. The vast amounts of CO_2 absorbed by the oceans causes acidification, influencing the health of our oceans and those whose livelihoods and nutrition depend on them (FAO, 2018b).

Climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change is also projected to have some potential benefits (IPCC, 2014).

Food security is high on the global policy agenda. Demand for food is increasing as populations grow and gain wealth to purchase more varied and resource-intensive diets. It has further been observed that in an increasingly globalized world, food insecurity in one region can have widespread political and economic ramifications (Garnett et al., 2013). There is increased competition for land, water, energy, and other inputs into food production. Climate change poses challenges to agriculture, particularly in developing countries and many current farming practices damage the environment and are a major source of greenhouse gases (GHG).

2.2 Climate Smart Agriculture

Climate smart agriculture (CSA) is a system of agriculture that promotes the actions that should be put into place to ensure agriculture supports development while ensuring food security amidst the threat of climate change.

Climate change is estimated to have already reduced global yields of maize and wheat by 3.8% and 5.5% (Iizumi & Ramankutty, 2015) respectively, and several researchers ((Dixon, 2012; McMichael & Lindgren, 2011) warn of steep decreases in crop productivity when temperatures exceed critical physiological thresholds. Increased climate variability exacerbates production risks and challenges farmers’ coping ability.

Climate change poses a threat to food access for both rural and urban populations by reducing agricultural production and incomes, increasing risks and disrupting markets. Lipper et al. (2014), notes that subsistence farmers, the landless and marginalized ethnic groups are particularly vulnerable to effects of climate change. Climate change alters agricultural production and food systems, and it is therefore necessary to transform agricultural systems to support global food security and consequently reduce poverty. Climate change introduces greater uncertainty and risk among farmers and policymakers, but need not lead to analysis paralysis an integrated, evidence-based and transformative approach to addressing food and climate security at all levels requires coordinated actions from the global to local levels, from research to policies and investments, and across private, public and civil society sectors to achieve the scale and rate of change required. With the right practices, policies and investments, the agriculture sector can move onto CSA pathways, resulting in decreased food insecurity and poverty in the short term while contributing to reducing climate change as a threat to food security over the longer term.

Agriculture faces some stiff challenges ahead. It has to address the fact that almost one billion people go to bed hungry every day, while more than two billion people will be added to the global population by 2050. In addition, food consumption patterns are changing as the average person in the world gets richer and consumes more food. There is increased competition for land, water, energy, and other inputs into food production. Climate change poses additional challenges to agriculture, particularly in developing countries. At the same time, Garnett et al. (2013), indicates that many current farming practices damage the environment and are a major source (19–29%) of anthropogenic greenhouse gas (GHG) emissions.

A study conducted in Nandi County, Kenya by Mutoko, Rioux, & Kirui (2015) on barriers, incentives and benefits in the adoption of climate-smart agriculture, identified Socio-economic and cultural barriers to adoption of CSA practices and also policy and institutional frameworks influencing adoption of CSA practices. The report further indicates that adoption of new technologies, innovations or practices take place within a socio-cultural environment and requires key capital inputs such as labour, finances, and social capital. Better organization and allocation of the various forms of capital would enhance efficiency important for the adoption and diffusion of interventions to achieve the desired impact in the farming system. Existing complementary policy and legal framework that stipulates focus on CSA practices would clearly guide how small-scale farmers who have adopted CSA practices such as agroforestry can also benefit from carbon credit schemes(Mutoko et al., 2015). Such policies need to be developed in sub Saharan Africa to ensure that countries have policy guidelines on CSA implementation.

2.3 Sustainable Intensification

Besides climate smart agriculture another adaptation technology is sustainable intensification (SI). Sustainable intensification approach entails increasing food production from existing farmland in ways that have lower environmental impact and which do not undermine the capacity to continue producing food in the future. Sustainable intensification and climate smart agriculture are highly complementary. SI is an essential means of adapting to climate change, also resulting in lower emissions GHGs per unit of output. With its emphasis on improving risk management, information flows and local institutions to support adaptive capacity, CSA provides the foundations for incentivizing and enabling intensification. But adaptation requires going beyond a narrow intensification lens to include diversified farming systems, local adaptation planning, building responsive governance systems, enhancing leadership skills, and building asset diversity. While SI and CSA are crucial for global food and nutritional security, they are only part of a multi-pronged approach that includes reducing consumption and waste, building social safety nets, facilitating trade, and enhancing diets (Garnett et al., 2013).

Food demand needs to be met from existing agricultural land, since opening up new land for agriculture carries major environmental costs. Intensification, without the sustainability focus, has led to numerous problems around the globe. Sustainable intensification does not mean business-as-usual food production and marginal improvements in sustainability, but rather a radical rethinking of food systems not only to reduce environmental impacts but also to enhance animal welfare and human nutrition and support rural economies and sustainable development. Add your own sentence as part of literature review-bring out the missing gap.

2.4 Crop and Livestock Farming in Embu County

Embu County heavily relies on the agricultural sector both as the principal source of food and nutrition and as the backbone of the economy just like the rest of the country. The total area under food crops is about 63,760 hectares (Ha) while the area under cash crops is about 18,969Ha as reported by the county government in their first CIDP document of 2013. This area combined accounts for approximately 30% of the total land in the County. The average farm sizes range from 1.98 acres for small-scale farmers especially due to continued land fragmentation to 7.4 acres for large scale farmers.

The main cash crops grown in Embu are Coffee, Tea, Macadamia and Cotton while the main food crops grown includes maize, dry beans, Irish potatoes, sweet potatoes, cassava, green grams, cowpeas, sorghum and millet. Farmers in the lower altitude areas of the county which are relatively drier than the higher altitude areas grow drought tolerant crops such as green grams, cowpeas, sorghum and millet. In the highlands the farmers have smaller portions of land since they are densely populated and fragmentation over time has resulted in smaller pieces of land. There some smallholder irrigation practices in the county with farmers mainly producing vegetable crops such as kales, tomatoes, cabbages, capsicums and spinach. The small irrigation schemes usually combine both rain-fed and those that rely on irrigation water mainly from the major rivers and streams mentioned earlier (MoALF, 2016).

Rearing of livestock is also a major economic activity in Embu. The farmers here keep both dairy and beef cattle as well as poultry, fish, rabbits, sheep and goats. There was project dabbed the Economic Stimulus Programme where the government facilitated construction of 8000 fish ponds that provide fish for local market. This was as reported by the ministry of Agriculture in the county in 2014. Farmers in this County tend to diversify their agricultural investments by practicing activities such as bee keeping (Chipeta, Henriksen, Wairimu, Muriuki, & Marani, 2015).

70% of Embu's population's livelihoods largely depend on agriculture, that is crop production and livestock keeping. The key value chain commodities produced by the majority of farmers are maize (61-100% of the farmers), followed by dairy cattle (41-60%) and banana and beans (21-40%) which contribute to both household food and livelihood security. In spite of the importance of agriculture, an estimated 20% of households are considered food insecure. Food insecurity peaks between the months of April and June, when harvested stocks have been depleted. This is mostly experienced in the hot and dry semi-arid lower zones of Mbeere North and South (MoALF, 2016)

2.4.1 Food Security in the County

FAO considers food security as a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life. In a household case, food security is the application of this concept of food security (physical, social and economic access to sufficient, safe and nutritious food) to the family level, with individuals within households as the focus of concern. On the other hand, food insecurity exists when people do not have adequate physical, social or economic access to food as defined above (FAO, 2003)

Food insecurity in Kenya is still high despite efforts to combat it. About 25% of Kenya's population is undernourished with about 15% of them requiring emergency food assistance annually. The Country's strategies to address food insecurity are broad based and their implementation is highly dependent on research-based information on food security that is focused on a specific agro-ecological zone (AEZ) (Ndirangu, Mbogoh, & Mbatia, 2017)

Food insecurity in the County is contributed to by a combination of factors that include climatic conditions, extreme weather and climate shocks, natural resource management, and access to appropriate agriculture related inputs. Water is a constraining factor that limits productivity for both crop production and livestock rearing especially in the drier areas of the County. Out of the total arable land in the County, only 5% is under irrigation and there is great potential to expand the irrigated area through water harvesting and storage in ponds and pans. There are some non-governmental organisations that have been promoting water harvesting in the County and this has been a major boost to food security especially in the drier areas (MoALF, 2016)

There is notable over reliance on rain-fed agriculture which renders farmers in the County susceptible to climate shocks that have increased due to climate change. Historical data records and reports indicate that both dry spells and extreme cases of rainfall keep recurring in the County. Dry spells (January to Early March) during the second wet season that occurs between October and December average around 65 consecutive days of moisture stress. Extreme precipitation and flood risks are quite high on average in both seasons (MoALF, 2016)

Farmers in the area practice several farming systems including the recently introduced technologies of coping with climate change. Some of the most widely used coping mechanisms are; soil and water conservation, planting of both indigenous and the exotic tree varieties, crop rotations and rain water harvesting technologies. Female headed households in these county tend embrace the water harvesting methods since this greatly reduces the time spent fetching water for livestock and domestic purposes and the methods also ensures reliability and availability of water for the household uses. On the other hand, the male headed households more likely invest in longer term strategies to improve the farm output and harvests and ensure sustainable production through growing of various types of crops. (MoALF, 2016).

As reported in 2014 by the Agricultural Sector Development Support Program ASDSP which operates in Embu County under the Ministry of Agriculture and Fisheries, the main sources of information on farming and agriculture in general for the farmers in the County are traditional, indigenous knowledge and radio which provide information to over 70% of the County dwellers. (Chipeta et al., 2015)

There are several non-governmental organisations that offer training, extension services, field days, offering Agricultural credits and market information to farmers in Embu County. These organisations include; public organisations such as KFA, private sector, non-profit faith based organisation, local and international organisations. However, these organisations face several challenges in the line of delivering to the farmers that include and are not limited to; poor coordination and collaboration, poor infrastructure facilities and constraints related to access to resources. This poor coordination leads to duplication of initiatives and activities and also brings about some level of confusion to the farmers since at the end of the day they may get contradictory information from the various stakeholders (MoALF, 2016)

2.4.2 AquaCrop Model

Aquacrop model is a water-driven crop growth model that evolved from concepts of seasonal yield response to water that were taken in stages to a concept of normalized crop water productivity. In this case the relationships between the crop and the environment are based on a daily time step as described by Studeto in his paper in 2009. (Amiri, 2016). AquaCrop simulates the attainable crop biomass and the harvestable yield against the relative water use pattern. The model allows users to a wide range of viable field management practices including irrigation, use of mulches, weed control etc. The model also facilitates decision making process both for researchers and the small scale farmers across the globe. If well calibrated the model has a user friendly interface that enables use even by inexperienced researchers and farmers to enable water use management strategies to boost production (Ngetich et al., 2012).

The effects of water stress on the yield and the water use processes are simulated by impacting the rate of canopy growth, the stomata conductance, the canopy senescence which is basically the process of aging of the crop where the canopy cover declines, the process of root deepening, and lastly the harvest index. The effect of fertility and salinity on the crop growth and productivity are not directly simulated, instead the model AquaCrop provides default adjustments of the main crop parameters for several limiting fertility categories ranging from near optimal to poor. These adjustments are multipliers that are used to influence by reducing the canopy growth coefficient (CGC), the maximum Canopy Cover (CCx), CC, from the time when CCx is reached to the maturity of the crop, but only gradually, and WP* (Biomass per unit of accumulated water transpired) (Amiri, 2016).

The model requires a minimum data set available for the model to operate. The input data defines the conditions where the crop is going to develop (Darko, Shouqi, Haofang, Liu, & Abbey, 2016). There are basically six input files need by the model for successful simulation. The climate data that entails the minimum and maximum air temperature, Evapotranspiration-ETo, and rainfall data. The second type of data set required is the Crop data that entails the planting date, the plant population, time to maximum canopy cover, start of senescence and the harvest date. The crop file contains both the conservative parameters those that are not affected by location and climatic conditions and the user specific parameters also referred to as non-conservative parameters. The other data set necessary is the soil data, the management data, irrigation data in the case of irrigated agriculture and the initial soil water conditions.

The first specific objective of this study was to calibrate the model for running simulations. The version of the model used in this study was AquaCrop 6.1, which was released in May 2018. This latest version of the model has both English and French language interface unlike all the previous versions. During the initial stages of the research process and before release of the 6.1 version, the previous version 6.0 was used since it had the inclusion of the dry beans crop in the crop database unlike the previous versions.

For the purposes of achieving the main objective of this study which was to assess the yield response to water for dry beans (*Phaseolus vulgaris L.*) by simulation using the model, the subject crop had to be grown so as to determine the crop specific model parameters and calibrate the model for the study area environment. Since this study coincided with the crop growing season (long rains) in the study area of March to May, this provided a good opportunity for cultivating the research crop in the study are.

2.5 Models commonly used in crop yield response to water and other environmental crop parameters modelling

Agricultural systems models worldwide are increasingly being used to explore options and solutions for the food security, climate change adaptation, mitigation and carbon trading problem domains (Holzworth et al., 2014). The models have an important role in informing farmer practice and breeding strategies. Lately they also play a key role in guiding agricultural related government policies that aim at addressing challenges such as food security, climate mitigation and adaptation. Several models are used to model the relationship and interactions between crops and the environment. These include CROPWAT™ (FAO, 2018a), APSIM™ (initiative, 2018), CropSyst (Stöckle, Donatelli, & Nelson, 2003).

2.5.1 CROPWAT Model

CROPWAT is a computer program for irrigation planning and management, developed by the Land and Water Development Division of FAO (FAO, 2018a). Its basic functions include the calculation of reference evapotranspiration, crop water requirements, crop and scheme irrigation.

Through a daily water balance, the user can simulate various water supply conditions and estimate yield reductions, irrigation and rainfall efficiencies. Typical applications of the water balance include the development of irrigation schedules for various crops and various irrigation methods, the evaluation of irrigation practices, as well as rain-fed production and drought effects. The use of the CROPWAT model can provide useful insights into the design of irrigation studies and parameters selected for irrigation treatments (Smith, Kivumbi, & Heng, 2002). The CROPWAT model can adequately simulate yield reduction as a result of imposed water stress. It is able to account well for the relative sensitivity of different growth stages and able to reproduce the negative impact of water stress on yield. The model has an important attribute in that it allows extension of the findings and conclusions from studies to conditions not tested in the field. Therefore, it is suitable for providing recommendations to farmers and extension staff on deficit irrigation scheduling under various conditions of water supply soil, and crop management conditions. However, Smith were able to compare the seasonal and cumulative yield reductions calculated by CROPWAT with the measured yield reductions as shown in the Table 2.1, after (Smith et al., 2002). The authors were able to further establish that the simulated results reflected the impact that stress in the different growth stages has on yield reduction, i.e. stress at flowering leads to a larger yield reduction than stress at boll formation. The model is yield response to water oriented however, it has bias towards irrigated agriculture. This study focused on rainfed agriculture and the effect of application of mulch in the field management that CROPWAT does not consider and therefore was inappropriate for the study.

Table 2.1: Comparison of measured and CROPWAT simulated yield reductions for cotton

	Measured		**CROPWAT**	
			Yield reduction (%)	
Irrigation Treatment	**Yield (t/ha)**	**Yield Read**	**Cumulative**	**Seasonal**
Normal Watering (111)	3.31	0	0	0
Stress during veg. growth (011)	3.05	8	13	12
Stress at flowering (101)	3.01	9	14	16
Stress at ball formation (110)	3.13	5	6	6
Stress at all three stages (000)	2.29	31	28	31

2.5.2 The CropSyst Model

The Cropping Systems Simulation Model also referred to as CropSyst is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator. The model's objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. For this purpose, CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management (Stockle & Donatelli, 1997).

The model simulates crop growth over a unit field area in square metres. The growth of the crop is described at the level of the whole plant and organs. Integration is performed with daily time steps using the Euler's Method. The model consists of some sub-models including the nitrogen and water sub-models. The nitrogen budget in CropSyst includes nitrogen transformations, ammonium sorption, symbiotic nitrogen fixation, crop nitrogen demand and crop nitrogen uptake. Nitrogen transformations of net mineralization, nitrification and denitrification are simulated. The water and nitrogen budgets interact to produce a simulation of N transport within the soil. Chemical budgets (pesticides, salinity), including pesticide decay and absorption, are also kept and interact with the water balance. All balances within the model are checked at each time step and errors are reported in case of departures within set threshold values. The model is therefore capable of determining crop nitrogen demand as well as water demand. The model has a capability to also simulate crop response to salinity. The water budget in the model includes precipitation, irrigation, runoff, interception, water infiltration, water redistribution in the soil profile, crop transpiration, and evaporation. This withstanding this model was not appropriate for this study since it does not simulate the effect of soil cover (mulches) on evaporation and subsequent crop yields. It was therefore not appropriate for this study. Users may select different methods to calculate water redistribution in the soil profile and reference evapotranspiration. Water redistribution in the soil is handled by a simple cascading approach or by a finite difference approach to determine soil water fluxes. CropSyst offers three options to calculate grass reference evapotranspiration. In decreasing order of required weather data input, these options are: The Penman-Monteith model, the Priestley-Taylor model, and a simpler implementation of the Priestley-Taylor model which only requires air temperature. Crop ET is determined from a crop coefficient at full canopy and ground coverage determined by canopy leaf area index. Crop development is simulated based on thermal time required to reach specific growth stages. The accumulation of thermal time may be accelerated by water stress.

Thermal time may be also modulated by photoperiod and vernalisation requirements whenever pertinent. Daily crop growth is expressed as biomass increase per unit ground area. The model accounts for four limiting factors to crop growth: water, nitrogen, light, and temperature. Given the common pathway for carbon and vapour exchange of leaves, there is a conservative relationship between crop transpiration and biomass production. Following Tanner and Sinclair formula, daily biomass accumulation is calculated as:

$$B_T = K_{BT}\ T / VPD \qquad (2.1)$$

Where:

B_T is the transpiration-dependent biomass production in $Kg/m^2/day$

T is the actual transpiration in $Kg/m^2/day$,

VPD is the mean daily vapour pressure deficit of the air in kPa.

Four input data files are required to run CropSyst: Weather, Soil, Crop, and Management files. Separation of files allows for an easier link of CropSyst simulations with GIS software. A Simulation Control file combines the input files as desired to produce specific simulation runs. In addition, the Control file determines the start and ending day for the simulation, define the crop rotations to be simulated, and set the values of all parameters requiring initialization. The weather file includes information such as latitude, weather file code name and directories, rainfall intensity parameters (for erosion prediction), freezing climate parameters (for locations where soil might freeze), and local parameters to generate daily solar radiation and vapour pressure deficit values. The Soil file includes surface soil Cation Exchange Capacity and pH, required for ammonia volatilization, parameters for the curve number approach (runoff calculation), surface soil texture (for erosion calculation), and five parameters specified by soil layer: Layer thickness, Field Capacity, Permanent Wilting Point, Bulk Density, and Bypass Coefficient. The latter is an empirical parameter to add dispersion to solute transport, particularly when using the cascading approach for soil water redistribution. The Management file includes automatic and scheduled management events. Automatic events (irrigation and nitrogen fertilization) are generally specified to provide optimum management for maximum growth, although irrigation can be also set for deficit irrigation. Management events can be scheduled using actual date, relative date (relative to year of planting), or using synchronization with phenological events (e.g., number of days after flowering). Scheduled events include irrigation (application date, amount, chemical or salinity content), nitrogen fertilization (application date, amount, source- organic and inorganic-, and application mode- broadcast, incorporated, injected), tillage operations (primary and secondary tillage operations, which are basically related to residue fate), and residue management (grazing, burning, chopping, etc.). The Crop file allows users to select parameters to represent different crops and crop cultivars using a common set of parameters. (Stockle, 2018). For validation purposes the model has been applied in several regions and for several crops including; corn, wheat, barley, soybean, sorghum and lupins in such regions such as Western US, Southern France, Northern and Southern Italy, Northern Syria, Northern Spain, and Western Australia. There were broadly good results however coupled with some challenges. A summary of some statistical results obtained after some validation processes for several locations is presented in the Table 2.2 (Stockle, 2018).

Table 2.2: Summary of statistical results for comparisons of simulated and observed yields

Crop	**Location**			**N**	**Obs. Mean kg/ha**	**Sim. Mean kg/ha**	**RMSE kg/ha**	**RMSE/ Obs. Mean**	**d**
Wheat	Northern Syria	G	W/N	16	2180	2410	550	0.25	0.92
Wheat	Northern Syria	B	W/N	16	7310	7090	870	0.12	0.96
Wheat	Northern Syria	G	W/N	16	1750	2080	560	0.32	0.90
Wheat	Northern Syria	B	W/N	16	7190	7140	1030	0.14	0.92
Corn	Davis, CA ; Ft Collins, CO	G	W	28	9831	9026	724	0.081	0.95

	Davis, CA ; Ft Collins, CO	B	W	28	16460	16808	1246	0.076	0.954
Wheat	Logan, UT	G	W	18	4100	4261	443	0.108	0.979
	Logan, UT	B	W	18	8033	8460	1121	0.14	0.961
Wheat	Logan, UT	G	W/N	30	4946	4963	383	0.077	0.975
	Logan, UT	B	W/N	30	10293	10339	786	0.076	0.996

d = Willmott Index of Agreement, ranging from 0 to 1, 1 being perfect agreement, B = Biomass, G = Grain Yield, W = Water treatments were imposed, N = Nitrogen treatments were imposed. RMSE- Root Mean Square Deviation.

The mode of operation, input requirements and the output of the models discussed were studied and none qualified to fit in the aim of this study which was mainly to assess the yield response to water for dry beans and recommend potential measures to cope with the situation. They therefore were all disqualified,

2.5.3 FAO AquaCrop Model

AquaCrop is a crop simulation model developed by the land and water Division of FAO to address food security and assess the effect of environment and management on crop production. AquaCrop simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. When designing the model, an optimum balance between simplicity, accuracy and robustness was pursued. To be widely applicable AquaCrop uses only a relatively small number of explicit parameters and mostly-intuitive input-variables requiring simple methods for their determination. On the other hand, the calculation procedures are grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system (FAO, 2018a)

The model describes the interactions between the plant, the soil including the management practices and the environment. From the soil in the root zone the plant extracts water and nutrients, field management practices and fertility levels are considered since they affect the plant-soil interaction. The crop-soil system is linked to the atmosphere through the upper boundary which determines the evaporative demand (ETo) and supplies CO_2 and energy for the growth. Water drains from the system to the subsoil and the ground water table through the lower boundary. If the groundwater table is shallow water can move upward to the system by capillary rise. This interaction is described in Figure 2.1 (FAO, 2017).

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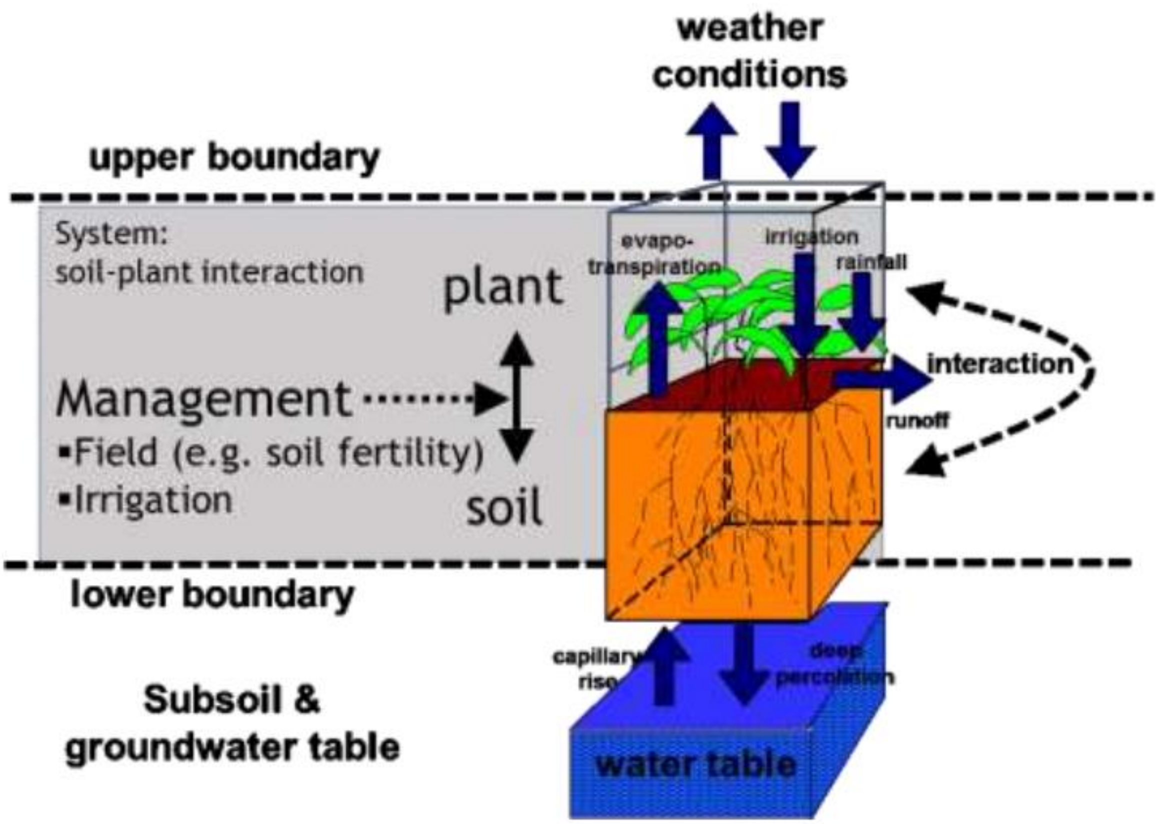

Figure 2.1: **The Root zone- Crop-Environment interactions as described in AquaCrop.**

Practical applications of AquaCrop Model

The model has several practical applications that include; use as a planning tool to aid in the management decisions for both rain-fed and irrigated agriculture, the model can also be used as an educational tool in understanding the crop response to environmental changes. It can further be used to compare attainable and actual yields in a field, farm, or a region, as a bench-marking tool. AquaCrop also informs about the constraint that limit crop production and water productivity, to develop strategies under water deficit conditions to maximize water productivity through; irrigation strategies: e.g. deficit irrigation; crop and management practices: e.g. adjusting planting date, cultivar selection, fertilization management, use of mulches, rain water harvesting. The model has a capability to help in studies of the effect of climate change on food production, by running AquaCrop with both historical and future weather conditions. The model can also be used as a planning tool as it analyzes scenarios that are useful for water administrators and managers, economists, policy analysts and scientists. (FAO, 2017)

The practical applications of the model are summarized in the following figure (Figure 2.2) adapted from (FAO, 2017).

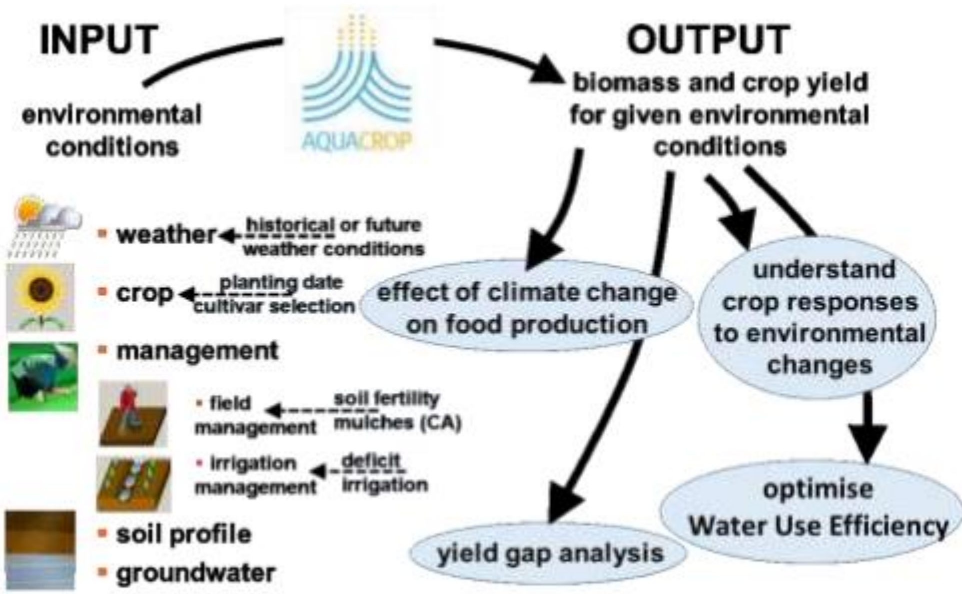

Figure 2.2: Practical applications of Aquacrop

In one sentence, show the link with your work

The Calculation Scheme of AquaCrop

The model simulates the final crop yield in a series of four steps. The four steps run in a series at each daily time step and consist in the simulation of; development of the green canopy cover (CC), crop transpiration (Tr), above ground biomass (B) and Crop Yield (Y).

Development of green canopy cover (CC)

Unlike other models Aquacrop expresses foliage development as green canopy cover (CC) and not as Leaf Area Index (LAI). The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (0% of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached (100 % of the soil surface covered by the canopy).

By adjusting daily the soil water content in the soil profile, AquaCrop keeps track of the stresses which might develop in the root zone. Soil water stress might affect the leaf and hence canopy expansion and if severe might trigger early canopy senescence. (FAO, 2017)

Crop transpiration (Tr)

For well watered conditions, Tr is calculated by multiplying the reference evapotranspiration (ETo) with a crop coefficient (KcTr). The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. Water stress does not only affect canopy development but might also induce stomata closure and hence affect, also directly, crop transpiration

Above-ground biomass (B):

The above ground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity (WP). In AquaCrop, WP is normalized for the effect of the climatic conditions which makes the ormalized biomass water productivity (WP*) valid for diverse locations seasons, and CO_2 concentrationsaffect (FAO, 2017)
.

Crop yield (Y)

The simulated above ground biomass (B) integrates all photosynthetic products assimilated by the crop during the season. By using a Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B. The actual HI is obtained by adjusting, during simulation, the reference Harvest Index (HIo) with an adjustment factor for stress effects. Temperature and water stresses directly affect one or more of the above processes as shown in the figure 2.3 (**FAO, 2017)**

AquaCrop considers also the effect of weed infestation, soil fertility and soil salinity stress on canopy development crop transpiration and biomass production. Where; CC is green canopy cover; Zr, rooting depth; ETo, reference evapotranspiration; WP*, normalized biomass water productivity; HI, harvest index; and GDD, growing degree day. Water stress: (a) slows canopy expansion, (b) accelerates canopy senescence, (c) decreases root deepening but only if severe, (d) reduces stomatal opening and transpiration, and (e) affects harvest index. Cold temperature stress (f) reduces crop transpiration. Hot or cold temperature stress (g) inhibits pollination and reduces HI. (FAO, 2017)

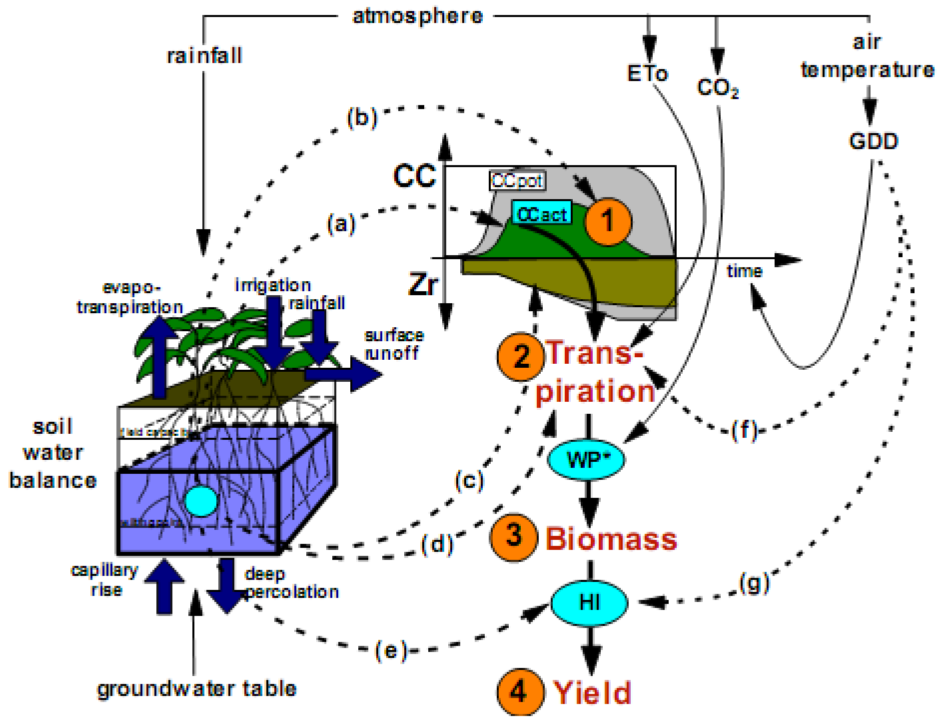

Figure 2.3: Calculation scheme of AquaCrop with indication of the 4 steps, and the processes (dotted arrows) affected by water stress (a to e) and temperature stress (f to g).

2.6 AquaCrop Input Requirements

The input data for the model includes; weather data, crop data, soil characteristics and the management practices that defione the environment bin which the crop will develop. The soil input parameters are divided into soil profile and groundwater characteristics and the management practices are divided into field management and irrigation management. The model input parameters are summarised in figure 2.4 (FAO, 2017).

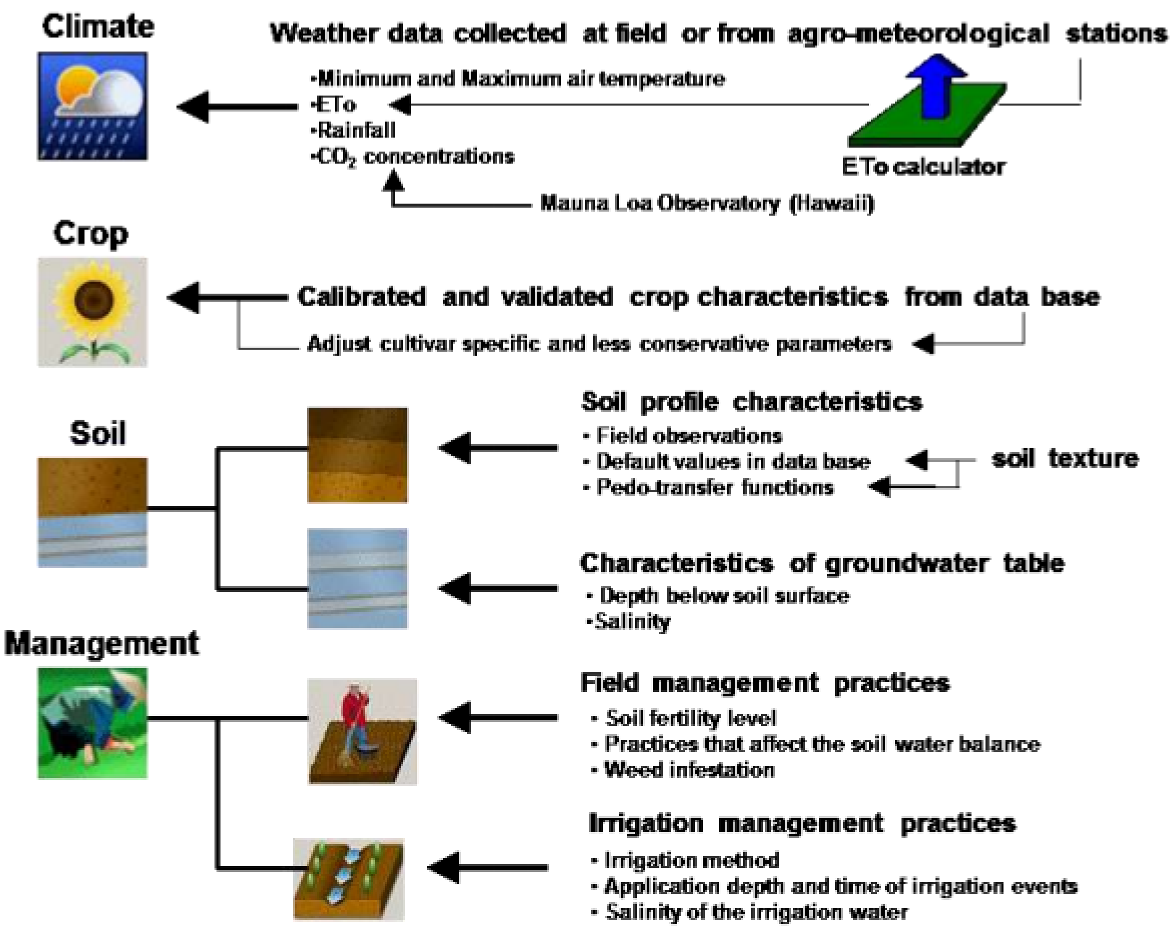

Figure 2.4: Required input data for AquaCrop

2.7 Limitations of AquaCrop

The model has a few limitations that; it simulates daily biomass production and final crop yield only for herbaceous crops which have a single growth cycle, AquaCrop is designed to predict crop yield at the single field scale (point simulations). The field is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics, and management and finally, only vertical incoming (rainfall, irrigation and capillary rise) and outgoing (evaporation, transpiration, and deep percolation) water fluxes are considered.

2.8 Calibration and Validation of AquaCrop Model

The model requires to be calibrated when running simulations for a specific cultivar and in a specific environment. Parameters that need to be specified are specific for a given cultivar and therefore might be affected by field management practices, conditions in the soil profile or the climate. Some of the parameters that need calibration include; calibration of crop response to soil fertility and crop response to soil salinity.

The model AquaCrop has a wide range of users across the globe who are interested in establishing the relationships between water availability, fertility levels, salinity levels and other climatic conditions and how they all relate to the yield levels of crops and biomass production. If the correlations between soil, water, plant, and atmosphere are well known, it is relatively easy to obtain needed climate, soil water capacity, texture, soil salinity, crop parameters, and agro technology data (irrigation scheduling, mulch, irrigation method, soil fertilization) and use the model. Based on model calibration and validation for local conditions, many researchers suggest that the model can be used to simulate plant production for practical purposes such as for better water management practices, sowing scheduling, and plant density (Stričević, Dželetović, Djurović, & Cosić, 2015).

In a study dubbed 'Application of the AquaCrop model to simulate the biomass of Miscanthus x giganteus under different nutrient supply conditions,' Stričević et al. (2015) focused on the measured data (root depth, crop phenology (the crop development stages), and the above-ground biomass by year of growth to carry out model calibration. The calibration results that were obtained showed a very good match between measured and simulated values. The largest and only significant difference was noted in 2008, when the crop was establishing and exhibited uneven radiation. The simulation results for the next 5 years showed a variance from 4 to 5.7%, believed to be a very good match. A high coefficient of determination (R^2 = 0.995) and high Willmott index of agreement (0.998) were also indicative of a good match between simulated and recorded biomass yields. The measured and simulated results for validated datasets at both locations were good. The average RMSE was 2.89 Mg/ha; when compared to the deviations noted at the test site itself, it was apparent that they were smaller in all the years of research except the first year. The index of agreement was 0.97 and the coefficient of determination R2 0.947. Based on model calibration and validation for local conditions, many researchers suggest that the model can be used to simulate plant production for practical purposes such as for better water management practices, sowing scheduling, plant density (Stričević et al., 2015). The authors summarized the statistical parameters of the model calibration and validation data sets for all years of research as shown in Table 2.2. After the validation, the coefficients of determination exhibited a good match in both calibrated and validated data sets.

Table 2.2: Root mean square error (RMSE), index of agreement (d), and R^2 for measured and simulated above-ground Miscanthus biomass.

Variables	Calibration Dataset	Validation Dataset
RMSE (Mg ha $^{-1}$)	0.896	2.89
D	0.998	0.973
R^2	0.995	0.947

In another study conducted to evaluate the performance of the model for simulating yield response of winter wheat to water on the southern Loess Plateau of China, the model was calibrated using measured data from three growing seasons from the year 2004 to 2008.

The Willmott index and the root mean square (RMSE) were used in the model validation process. They helped evaluate the goodness of fit between the observed data for grain yield, above ground biomass, water productivity, canopy cover and soil water content in the root zone and the simulated values for the same for the years 2008 to 2011 which was three growing seasons (Zhang, Liu, Xue, Chen, & Han, 2013).

Andarzian et al. (2011) conducted a study in a hot and dry environment of Southern Iran with the aim of Validating and testing the AquaCrop model under full and deficit irrigated wheat production in Iran. The author further investigated the effects of different scenarios of irrigation on wheat yields. The author evaluated the model with experimental data collected in three field experiments. In this study the model was able to accurately simulate soil water content of root zone, crop biomass and grain yield, with normalized root mean square error (RMSE) less than 10%. Since this study focuses on carrying similar crop growth parameter evaluations, it is expected that this model will perform this with a high degree of accuracy.

In another study conducted in the Río Dulce irrigation system, Santiago del Estero, Argentina to quantify yield and water productivity gaps in an irrigation district under rotational delivery schedule Morábito et al. (2015) focused on maize, cotton and alfalfa crops which are generally grown in the target district under irrigation. There was however a challenge since AquaCrop model does not simulate alfalfa and was therefore only used in the simulation of the yield and water productivity for maize and cotton. The model was calibrated for the two crops using experimental data collected between 2007 and 2012. In the study two sets of maize experiments were used: one related to crop response to deficit irrigation (100 % ET, 75 % ET, 50 % ET, 25 % ET and rain-fed), and the other one related to crop response to different sowing dates (October, November and December). It turned out that the conservative crop parameters were adequate for the cultivars and conditions in Santiago del Estero. Less conservative crop parameters, such as harvest index (HI, 47 %), time from sowing to maturity (1890°- days, GDD), plant density (80,000 plants ha^{-1}) and maximum canopy cover (96 %), were adjusted. For cotton, also two sets of experiments were used: one related to crop response to deficit irrigation (100 % ET, 75 % ET, 50 % ET, 25 % ET and rainfed), and the other one related to crop response to water excess (variable water gifts were given, simulating a normal, humid and very humid season). Also for cotton, conservative crop parameters, were adequate. Some less conservative parameters were modified, to simulate better the cropping practices and the behavior of the specific cultivars used in the cotton experiments: canopy growth coefficient (0.846 % GDD−1), canopy decline coefficient (0.62 % GDD−1), time from sowing to flowering (675 GDD), length of the flowering stage (747 GDD), length of building up of the harvest index (1020 GDD), time from sowing to start senescence (1364 GDD), time from sowing to maturity (1880 GDD), reference HI (41 %). In this study the simulations, for both maize and cotton the maximum rooting depth was set at 180 cm (Angella, 2015) .

2.9 Simulation of yield response to water and yield potential

There's inadequate information from literature on the simulation of yield response to water using this model. However, a few studies have been conducted to assess this using the model. The Aquacrop model is developed on the basic relationship of yield response to water that was first developed by Doorenbos & Kassam, (1979) but has evolved to a daily-step process-based crop growth model with limited complexity as simplified in the Equation 2.2.

$$\frac{Yx-Ya}{Yx} = ky\left(\frac{ETx-ETa}{ETx}\right) \qquad (2.2)$$

where Y_x and Y_a are the maximum and actual yield,

ET_x and ET_a are the maximum and actual evapotranspiration, and

k_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

The model is based on a water-driven growth module, in which the crop transpiration is converted into biomass through a water productivity parameter. This could be conceptualized in terms of Equation 2.3 (Jingjing WANG, 2015).

$$B = WP \times \sum T \qquad (2.3)$$

Where:

T is the crop transpiration (mm);

B is crop biomass;

WP is the water productivity (kg m^{-3}) (biomass per unit of cumulative transpiration), which tends to be constant for a given climatic condition.

In a study conducted to evaluate the performance of the model for simulating yield response of winter wheat to water on the southern Loess Plateau of China several findings were made. In the study multi-year field experimental data from 2004 and 2011 were used to calibrate and validate the model for conducting simulations of biomass, canopy cover, soil water content and like this study focused to achieve the grain yield under rainfed conditions. This was a study closer in methodology to this study since the crop growing was rainfed. After evaluation of the model using the root mean square error and the Willmott index of agreement the RMSE ranged from 0.16 to 0.38 t/ha for simulating above ground biomass, 1.87 to 4.15% for CC, 0.50 to 1.44 t/ha for grain yield, and 5.70 to 22.56 mm for soil water content. The “d” ranged from 0.22 to 0.89, 0.25 to 0.43, 0.36 to 0.62 and 0.95 to 0.98 for above ground biomass, CC, soil water content and grain yield, respectively. It was established that the model performed better in simulating crop cover denoted (CC) and the grain yield than in the simulation of biomass and soil water content. Wanhong further established that the model is suitable and capable of simulating winter wheat yield under rainfed conditions. The author further recommends a consideration of different management practices such as fertility levels and irrigation levels for improved results (Zhang et al., 2013) .

2.10 Yield Gap Analysis using AquaCrop Model

The model can be used to determine the potential and attainable yields of crops under different management scenarios. This feature made it useful in the current study focusing on the production of dry beans in the study area.

In a study conducted by (Morábito et al., 2015) aimed at Quantifying yield and water productivity gaps in an irrigation district under rotational delivery schedule, AquaCrop model was used to determine the potential and attainable yields of maize and cotton under various water management scenarios. Simulations were done using AquaCrop under different conditions and the following variables obtained; yield (Y), harvest index (HI), the ratio of actual transpiration to the maximum transpiration that could be achieved without stomatal closure (T_{ra}/T_{rx}). irrigation (Irr), drainage (Dr), relative drainage index (IDr, which was calculated as the ratio of the drainage in a given production level and the drainage under potential production), water productivity (WPet, which was defined as the ratio of crop yield to crop evapotranspiration, ET), and irrigation water productivity (IWP), the latter was calculated as the yield difference between simulated irrigated and rainfed conditions divided by the gross irrigation. The Actual yields and irrigation practices were determined by field surveys and farmers' interviews. The AquaGIS tool facilitated the assessment of the spatial and temporal variations in yield using a daily climatic database of 26 years. The average yield gap which was obtained by getting the difference between the potential and the actual amounted to 6 t ha^{-1} in maize and 2 t ha^{-1} in cotton. The average water productivity gap was 7 kg ha^{-1} mm^{-1} in maize and 2 kg ha^{-1} mm^{-1} in cotton. Morábito et al. (2015) established that by employing a more effective use of the rotational delivery schedule, the yield gap could be partially closed in particular if associated with other agronomic practices. The author was able to demonstrate the potential of combining field data collection with the use of AquaCrop to quantify the yield and water productivity gaps, and to propose management recommendations for closing the gaps (Morábito et al., 2015)

2.11 Critic of literature

Most of the studies conducted on the yield response to water using AquaCrop have not considered the dry beans crop that this study considers. Most of studies using Aquacrop are based on maize, wheat and rice production. This study took the advantage of the recent inclusion of dry beans crop in the model database which was previously not available. The crop being a main source of food for families in the study area including a major food in institutions in the County of the study area it was important to model various scenarios that the crop is grown under and recommend the best that yields the best results. With the recent negative impact of climate change in the area the crop has suffered a decline in the yield levels leading to subsequent reduction in the level of incomes for the families since any surplus harvest is usually sold to traders.

Bello & Walker (2016) conducted a research on the validation of the AquaCrop model for pearl millet which is grown in some of the driest regions of the world. While conducting simulations Pearl should have considered the influence of the application of mulch on the cultivation of millet ion the dry conditions (Bello & Walker, 2016). This study puts into consideration the application of mulches in the cultivation of beans since the model is calibrated for dry areas and dry land variety of beans.

Most studies using the AquaCrop model are based on irrigated agriculture. Darko, Shouqi, Haofang, Liu, & Abbey, (2016) used the model in his study to calibrated and validated the model for deficit and full irrigation on tomato crop in central region Ghana. In his study the authors considered irrigated tomato and the crop was cultivated under rain shelter to ensure no rainfall on the crop. During the simulation the rainfall file contained zero values for rainfall besides there being rain events in the area (Darko et al., 2016). This study was based on rain-fed dry beans cultivation based on two cultivation systems in the study area. However, after calibration some simulations were done with consideration some level of irrigation to mimic the situation that happens towards the end of rain seasons in the study area usually occasioned by a crop failure.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study area

The research project was conducted in Mbeti North ward, Embu West Sub-County, Embu County, Kenya. The GPS location at the centre of the model crop growing site was 0.5403S, 37.5464E at an elevation of 1333m ASL. This area was selected due to its unique climatic conditions depicting up to eight AEZs unlike most other parts of the Country. The area has also a bimodal rainfall pattern annually and the long rains of March to May coincided with the time for this study. The cultivation of dry beans as a value chain comes in third after maize and banana as reported by the County Government in its 2013 County Integrated Development Plan (CIDP). Being a shorter period crop and equally important in the area the study was conducted on dry bean (*Phaseolus vulgaris L*) crop of KAT B1 variety. The seeds were sourced from the KALRO Embu station office who are certified dealers.

3.1.1 Location, Geography and Demographics

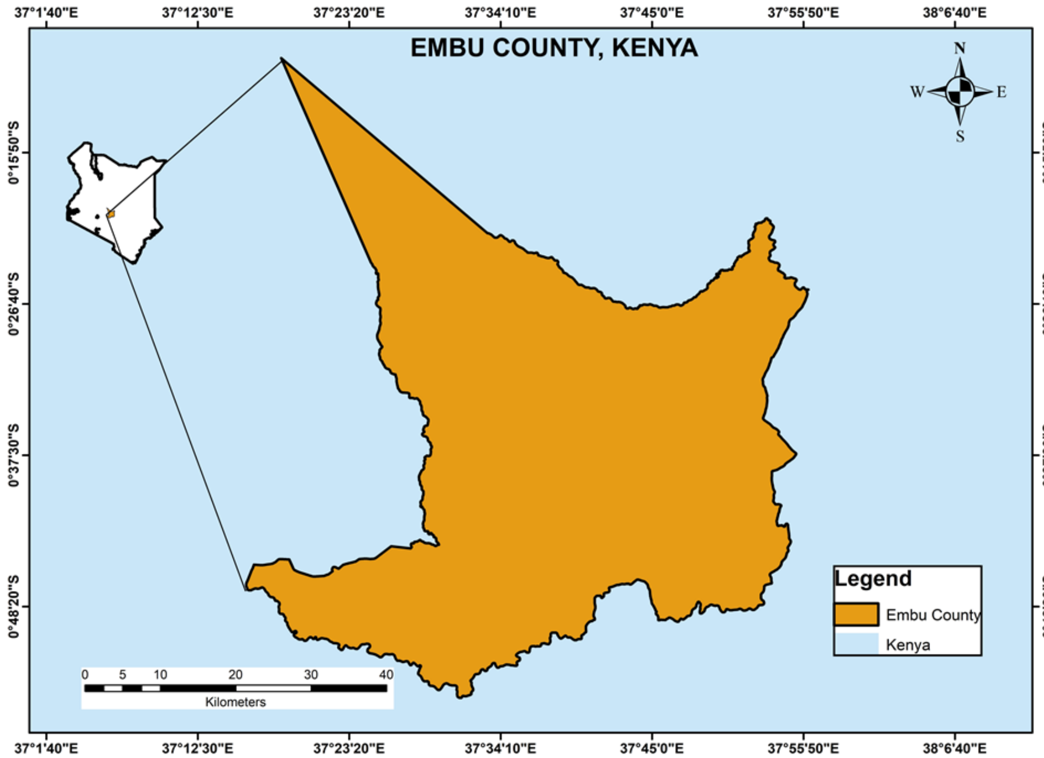

Figure 3.1: **Map of the study area**

Embu County is one of the 47 Counties which are devolved government units of the Republic of Kenya. It is located in the former Eastern Province approximately between Latitude 0° 8'and 0° 50' South of the Equator and Longitude 37° 3' and 37° 9' East of the Prime Meridian. The County has a total land mass area of 2,818. km^2. Embu boarders Mt. Kenya to the North and therefore a high altitude area characterised by heavy rainfall throughout the year while stretching to the lower altitude area that is characterised by moderately arid to arid and semi-arid areas that receives lower amount of rainfall throughout the year. Embu rises from about 515m above sea level at the River Tana Basin in the East to 5,199m at the peak of Mt. Kenya in the North West.

The southern part of the county is covered by Mwea plains which rise northwards, culminating in hills and valleys to the northern and eastern parts of the county. There are also steep slopes at the foot of Mt. Kenya. There are six major rivers that traverse through the county namely: Thuci, Tana, Kii, Rupingazi, Thiba and Ena. Tana river being the main drainage channel all the other five rivers are its tributaries. Along the Tana river and within the County lies some power generation dams that include; Masinga, Kiambere, Kindaruma and Gitaru. Some of the dams extend to other Counties that border Embu (CGoE, 2013).

Formerly Embu town was the headquarter of the former Eastern Province and therefore the town is to date a cosmopolitan town with people from various tribes in Kenya. The county has a population of 577,390 people as per the KNBS year 2017 projection statistics. This translates to a population density of 221 persons per square kilometre. The North Easter areas of the county are more densely populated as compared to the lower areas of Mbeere (CGoE, 2013).

3.1.2 Agro-Ecological Zones

Agro Ecological Zoning is the division of an area of land into smaller units, which have similar characteristics that are related to land suitability, potential production and environmental impact. An Agro-ecological Zone (AEZ) is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use. The agricultural land in Kenya is classified into zone groups based on maximum temperature limits and water requirements within which the main crops grown in Kenya can flourish (Ndirangu et al., 2017).

The agricultural potential in Embu County is largely influenced by the eight distinct Agro-Ecological zones (AEZ) that are present in the area. This is due to the thermal and altitude dependent conditions from the hot and dry semi-arid lower zones in the Tana River Basin in Mbeere North and South, to the windward side of Mount Kenya that is cold and wet in most times in a year. The cold and wet areas that are majorly tea zones include Runyenjes, Kianjokoma and Manyatta areas. The agro-ecological profile is typical of the windward side of Mt. Kenya from cold and wet upper zones to hot and dry lower zones in the Tana River Basin. Embu has a bi-modal rainfall pattern with two distinct rain seasons. The long rains occur between March and June while the short rains fall between October and December. The annual rainfall in the County averages from as high as 2200mm at the highest altitudes of around 2500m ASL to as low as 600mm near the Tana River at 700m ASL. Temperatures in the County range from a minimum of 12˚C in the month of July to a maximum of 30˚C in March. July is usually the coldest month with an average of 15˚C while September is usually the warmest with an average monthly temperature rising to 27.1˚C. However, some parts of the County have unique micro climatic conditions for instance the areas around the dams mentioned above (CGoE, 2013) . The ecological zones present in the County are as stipulated in table 3.1 below and follows a map showing the different AEZs.

For purposes of modelling with the AquaCrop model, the dry bean crop was cultivated in the UM 4 region of the AEZs in the area. This was selected since majority of farmers in this region cultivate beans on large portions of land for food and for the market as reported by the department of agriculture in the County (CGoE, 2013).

Table 3.1: Ecological Zones in Embu County source; (MoALF, 2016) and (Embu County Government, 2013)

Zone	Climatic Conditions	Vegetation/Crops/livestock
UH 0	Cool and Wet	Forest
LH 1	Moderately Cool and Wet, high rainfall	Tea, Dairy cattle
UM 1	Warm and Humid	Coffee, Beans, Maize, Banana
UM 2	Warm and Humid	Main Coffee zone, maize, Banana
UM 3	Warm and Humid	Marginal Coffee zone, Maize, Beans, Banana
UM 4	Warm and semi humid	Sunflower, Maize, Dry land Beans
LM 3	Hot and dry	Sorghum, livestock, Cotton
LM 4	Hot and dry, semi-arid	Marginal Cotton zone,
LM 5	Hot and dry, semi-arid	Livestock, Millet Zone

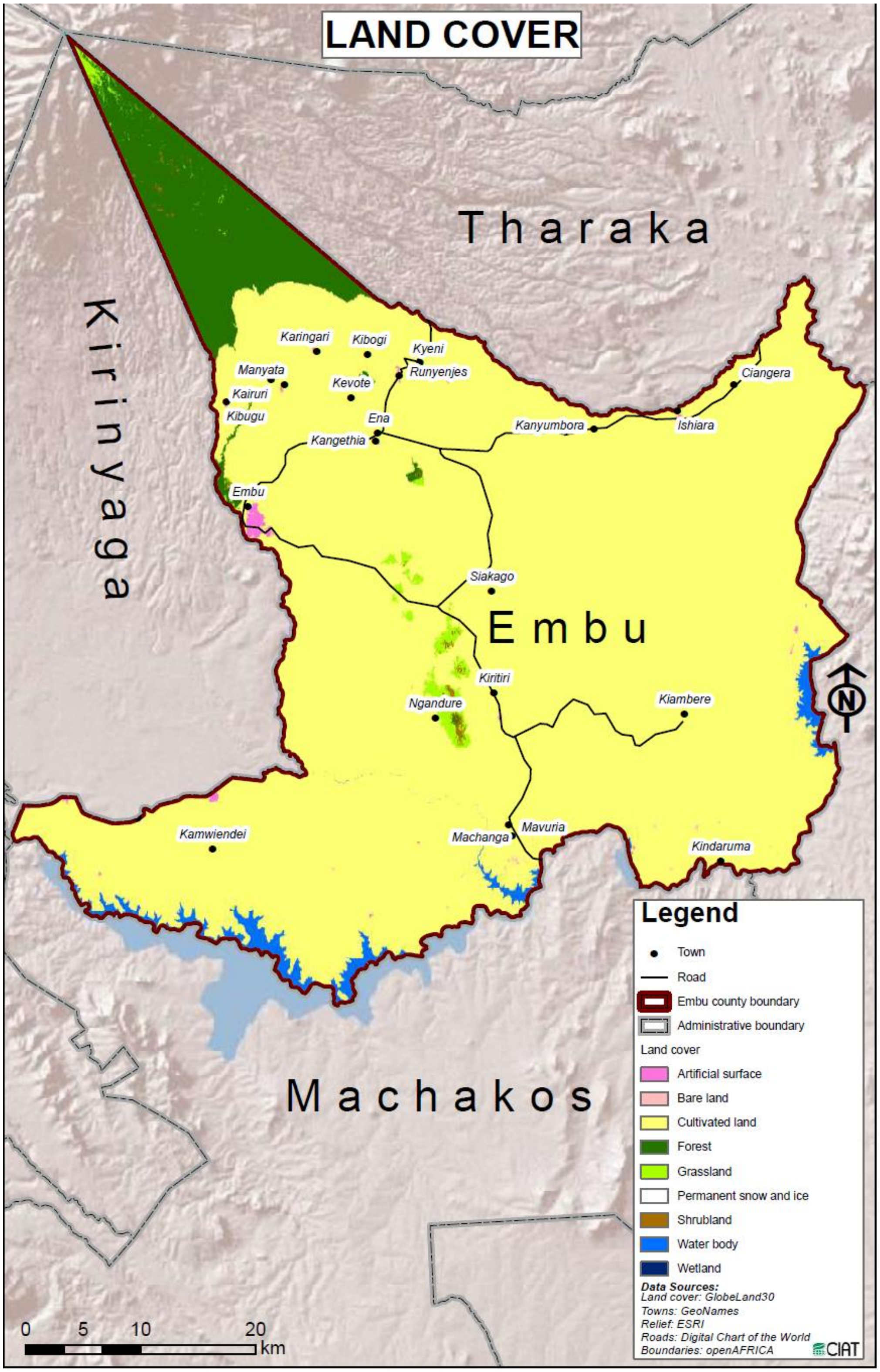

Figure 3.3 A map showing the Various types of land cover in Embu County

3.3.1 Site selection

The site for the cultivation of the crop was selected within the identified farm and a land portion measuring 30m by 20m was leased out for the purposes of growing the crop. The portion was carefully selected and met the following criteria: well drained with a gentle slope, away from buildings and trees, not a virgin land, not tilled in the past two seasons, clear without thick bushes, not recently applied with chemical fertilizers, free from any soil borne diseases. It was important to ensure that the area was gently sloping so as to ensure that the plots were free from flooding to avoid rotting of the crop. This is a requirement in the cultivation of beans.

The plots were located away from tall trees and buildings to avoid the shading effect that would interfere with the growth of the crops. Tall buildings, trees and fences could also bring about the rain shadow effect. The area selected had to previously not had been a virgin land since virgin lands in the area whose previous land cover was mainly grass had shown trends of low levels of nitrogen and beans would perform poorly on such farms as reported by KALRO Embu station. However, the virgin lands with a previous land cover of *Lantana camara L*. locally referred to as 'mucumoro' had recorded high yields of beans. Since the study was intended to consider the case of conservation agriculture (CA) as one of the treatments, the selected area needed to have not been tilled for the previous two crop growing seasons to ensure that there was no recent soil disturbance in the area.

3.3.2 Field Trials

For the purposes of both calibration and validation of the AquaCrop model used in this study, a field experiment was conducted by growing a crop of dry beans. The crop, soil, management and environmental data for the locality were used in fine tuning the cultivar specific model parameters. Once was the fine tuning and calibration was done using the data from the area, the model would later be used in running simulations. One of the drawbacks in this study was the fact that there was only one cropping season that coincided with this study for crop data collection.

Figure 3.4: **Site Selection Exercise**

3.3.2 Preliminaries, Farm Inputs and Crop Cultivation

The required farm inputs and were procured locally within the town of Embu and those unavailable were conveniently sourced from the nearby agro–dealer outlets. The seeds were sourced from Kenya Agricultural and Livestock Research Organisation (KALRO) Embu approved stockist with the certified KAT B1 seeds. Prior to the purchase of fertilizers, and manure a soil fertility test for the piece of land was conducted aimed at informing the soil nutrients levels and any deficiencies and provide recommendations based on the cultivation of beans since this study was intended to have treatments where fertility was not a limiting factorSoil sampling was conducted using guidelines provided by (Carter & Gregorich, 2008)). The soil sample collected was delivered to the Kenya Agricultural and Livestock Research Organisation's Soil Laboratories in Nairobi Kenya for analysis. The other inputs included pesticides, DAP fertilizer, compost manure, demarcation strings, soil sampling equipment and labour that was to be provided throughout the crop growing season.

Clearing of the portion of land was done using simple tools such as machetes. The clearing included shallow weeding and uprooting of weeds since the long rains had started a few weeks before, weeds had already germinated. Soil sampling for fertility tests and soil sample delivery to the labs was conducted prior to planting of the crop.

On the 30m by 20m area selected above, 8 plots each measuring 5m by 5m were set out for the purposes of growing the crop under various treatments as discussed in section 3.4. The plots were centrally located so as to allow for some room on all the edges for planting a barrier crop. The barrier perimeter crop was intended to push away the pests as well as attracting them since it was to be of the same variety. Barrier perimeter crops are a type of trap crops used as a border to protect another crop from pests and diseases by acting as a 'sink' (Gabryś & Kordan, 2013). The barrier crop was planted a week before the main crop was planted as recommended by (Rea et al., 2002). This was to allow it grow earlier than the main crop so that it could attract any pests targeting the main crop.

The crop planting exercise was conducted on the 4th day of April 2018. The Aquacrop model requirement was that soil moisture content be determined on this day since the intention of the study was to have the start of the simulation as the planting date of the crop. This meant that a soil sample for moisture analysis on the day of planting across the soil profile was to be collected. Along this, soil samples for the soil classification analysis, determination of the soil porosity, Bulk density and the hydraulic conductivity of the soil in the field were collected on the this planting day. The soil sampling approach employed for the bulk density and porosity samples was as recommended by the institute of Agriculture and Natural Resources of the University of Nebraska. The samples collected were delivered to the soil laboratory for purposes of measurements. Figure 3.3 shows some photos taken during the soil sampling exercise.

Figure 3.6 Soil sampling for bulk density and porosity exercise. Source: (Author 2018)

On the 30m by 20m area selected above, 8 plots each measuring 5m by 5m were set out for the purposes of growing the crop. The beans were planted at the spacing of 60cm by 20cm planting two seeds per station. The planting was done in small furrows of an average depth of 5cm. This was as recommended by Kenya Agricultural and Livestock Research Organisation Embu station for this region. The furrows and ridges formed are meant to enhance water infiltration into the soil since they slightly hold water before runoff forms. The seeds were drilled to an average depth of about 2.5 to 3cm. (University of Illinois Extension, 2018). The compost manure and the fertilizer had previously been well incorporated into the soil prior to planting. The manure was added at the rate of 4tons per hectare as had been recommended by the KALRO laboratory soil fertility test results. The plant population per the 5m by 5m plot was 417 plants and the corresponding plant density was 834,000 plants per Ha. This was calculated using the formula recommended by Adebooye, Ajadi, & Fagbohun (2006) in a paper describing "An Accurate Mathematical Formula for Estimating Plant Population in a Four Dimensional Field of Sole Crop". The equation 3.1 below was applied in the calculations.

$$Pp = \left(\frac{10{,}000m2\ x\ number\ of\ seeds\ per\ stand}{Product\ of\ spacing\ (m2)}\right) \qquad (3.1).$$

Where Pp is the Plant Population

3.3.3 Crop and Soil parameters data collection

Crop and soil parameters were directly recorded on the field at the study site. Crop parameters such as the date of sowing, days from sowing to germination, plant density, time to full canopy cover, the start and end of the flowering period in days, start of the senescence, days to maturity, complete drying of the crop after maturity, the plant density at planting and at maturity were all observed and recorded throughout the entire season. The plant density at planting was calculated as per equation 3. 1. The dry beans grain yield quantities per research plot were measured at 13.5% moisture content. The moisture content at harvest was measured using GMK 303RS grain moisture meter. After harvest the grains were further dried under natural conditions since the average moisture level per plot at harvest was 16%. The moisture meter was instrumental in ensuring that the final recorded mass of grains was at 13.5%.

Figure 3.7: Grain Moisture measurements during harvest

Fraction of canopy cover was determined by taking digital photographs from pictures above the plants at midday for determination of canopy cover percentage. Above ground biomass yields were determined on dry weight basis after harvesting and sun drying until constant weight.

The soil moisture content was determined at the day of planting and subsequent moisture levels were determined by the model using the relationship between rainfall and the evapotranspiration. The initial plan was to have some moisture sensors in a PVC access tube installed in the middle of the study site however, this was an expensive gadget that was not locally available with an estimated cost of 2,000.00 USD.

The soil horizons were established by taking a 0 to 1m soil section. The soil horizons were delineated based on the homogeneity of colour, texture using the feel method and the general soil appearance done by observation. (Ngetich, 2012). The soil texture and the organic carbon were determined in the KALRO laboratories upon submission of the soil samples.

3.3.4 Climate Data

The climate data considered in this study and that formed the model input data included; included Rainfall amount, minimum and maximum temperature, Evapotranspiration ETo, and the concentration of Carbon dioxide (CO_2). The default CO_2 file available in the model database was used for this study. The rainfall amount, the minimum and maximum temperature data and Evaporation data for the crop growing season were obtained from the Kenya Meteorological

Department Embu weather station. The daily ET_o was calculated using the inbuilt model ET_o calculator that uses the Penman Monteith equation to do the calculation. This was aided by the availability of the minimum and maximum air temperature data. For the missing wind speed data, the ET_o calculator default value for light to moderate winds was specified. The missing humidity data was estimated by the calculator which tackled this by assuming that the minimum air temperature is a good estimate for the mean dew point temperature. For the net radiation this study used a value of 0.16 for interior locations which was used for a similar study in the area by Ngetich et al. (2012).

3.4 AquaCrop Model Calibration

Amiri (2016) in his paper on the calibration and testing of AquaCrop model for rice under water and Nitrogen management, defines model calibration as the process of adjusting certain model parameters to make the model match the measured values at the given location. In this study the crop data collected was used in calibrating the model. The crop parameters in the model, were fine tuned to the local conditions for the purposes of customizing it to be able to conduct simulations for the study crop in the specific study area.

The initial canopy cover (CC_0) which is usually given as a percentage was estimated from the planting density of the crop (Amiri, 2016). The subsequent canopy expansion rates were automatically estimated by the AquaCrop model after inputting parameters such as the planting method used and phonological dates such as the days to reach 90% seedling emergence, days to maximum canopy cover, time to start flowering or the start of yield formation, the flowering duration, days to the onset of senescence, days to maturity of the crop all of which were recorded at the site during the growing period (FAO, 2017).

Some of the crop parameters were assumed to be conservative therefore their values were not changed in the model database for instance the normalized biomass water productivity and the thresholds for water, salinity and fertility stresses, while the user-specific parameters for this study were obtained from the crop data recorded during experiment.

After fine tuning the cultivar specific crop parameters, the growth pattern of the crop was converted from calendar time into thermal time (Growing degree days). In this the length and the duration of the bean crop development stages was adjusted to the temperature regimes of the distinctive years that the simulation was to consider (FAO, 2017). Once all the input files were adjusted in the model the model calibration was done. The model was validated by adjusting the calibration to the actual yields obtained in the cropping season.

3.4.1Creating the input files

The main menu of AquaCrop consists of two panels where the names and descriptions of the selected input files are displayed. On the environment and crop panel the climate, crop, field management, soil profile and groundwater table files were input with the corresponding parameters for the study area. On this same panel the start of the growing cycle was specified. The model stores these data files separately in the database as follows; temperature files with extension ".Tnx", ETo files with extension ".ETo", Rainfall files with extension ".PLU", and the CO_2 files with extension ". CO_2". (FAO, 2017)

Climate Data input file; Rainfall, Temperature (min and max), ETo and CO_2

The climate data files for all the above climatic parameters were created according to the steps outlined in (FAO, 2017) AquaCrop user manual. This was done by selecting the climate command and subsequently the 'select/ create climate file' command in the file management panel that is found on the main menu. The option for importing climate file was used since data had been obtained from the met station in excel sheets. The data used in this study was daily data and this was specified on the model menu.

The default assigned CO_2 file was used in this study since the simulations were to only consider the near future which is within a period of ten years. The default assigned 'MaunaLoa.CO2' file was used. The file is stored in the 'SIMUL'subdirectory of the model. This file contains the mean annual atmospheric CO_2 concentration that was measured at Mauna Loa observatory since the year 1958. (FAO, 2017).

Soil Profile File

The soil profile file was created in the 'create soil profile file menu. The number of horizons were specified. The soil textural class and the thickness of each horizon were also specified. The soil class was selected among the default soil classes available in a list on the model's soil profile file input section. The soil physical characteristics of each layer are then derived having provided the soil parameters above. Having tests for the soil from the study site evaluated from the KALRO soil laboratory, the model derived parameters were compared and verified. The soil water content at permanent wilting point (θ_{PWP}), at field capacity (θ_{FC}) and at saturation (θ_{SAT}) were obtained from the model indicative values using the soil textural class that had been determined in the laboratory. The saturated hydraulic conductivity for the soil at the study site was also derived from the model using the already known soil class. The soil at the study site did not have any restrictive layers or hardpans across the soil horizon. The groundwater table level in the area was assumed to be way more than 4m therefore below the root zone area therefore there was no need to specify a groundwater table for this study. In this case the capillary rise was disregarded. (FAO, 2017)

3.5 Simulation of the dry beans grain yield response to water under varying field management scenarios

3.5.1 Creating files with Initial Conditions

Before conducting any simulation, the simulation period and the initial conditions at the start of the simulation were set as conducted by Darko in his study and by consulting the AquaCrop user's guides provided by FAO (Darko et al., 2016). A file containing the initial conditions at the start of the simulation was created.

Having conducted a soil profile sampling on the day of planting, the initial conditions in the model were adjusted as per the measured values for salt water content and the moisture content. This study intended to have the start of the simulation period coinciding with the day of sowing the seeds. This meant that the simulation was linked with the growing cycle. (FAO, 2017). Since soil moisture contents and the salinity levels were not tested for every soil horizon this study used the model predefined commands in evaluating the water and salt contents at various depths of the soil by ensuring that the correct soil profile file was selected. In this case the whole soil profile was put at a specific soil water content that is at field capacity and a specific salinity content. The initial crop parameters were set as discussed in section 3.2.2.5 above.

3.5.2 Conducting Simulations

Simulations were done after setting the initial conditions per scenario. This was done by selecting the "Run" button on the model. The simulations were conducted for every specified setting. The parameters that resulted from the model calibration process above were used for further simulation runs. The very first simulation was on the model calibration process as discussed above. The successive simulations were conducted under various management scenarios by adjusting each of the initial conditions under evaluation. In some cases, the values for the previous simulation runs were kept as the initial conditions for the succeeding run using the 'keep values from previous simulation' menu however for most runs this was reset to key in new conditions.

The simulations were conducted by altering the parameter under consideration under the management menu in the model.

Farmers Practice Scenario

Simulation for the farmers practice that entails; burning or removal of crop residue after harvest, land tilling using hoes and at times using ox-drawn ploughs. In this case crop rotation is not carried out. The simulation was conducted by choosing 'none' on the mulch menu under the field management menu on the model. Several alterations were done and simulations were performed.

Conservation Agriculture Scenario

Conservation Agriculture practice entails the use of organic mulch and in this case crop residues were applied in the field. The residues are left in the subsequent years to keep disintegrating in the soil adding organic matter and conserving moisture over the years. Crop rotation and zero or minimal soil disturbance are also done in the conservation agriculture practice. The simulations were done at various soil mulch application i.e. From 25-100%

Irrigation Scenario

Each of the two scenarios discussed under 3.3.2.2 and 3.3.2.1 above were simulated considering some various levels of irrigation towards the end of the growing season. This was considered since the study area usually experiences crop failure towards the end of most seasons in the recent years

Simulations for future years

These simulations were conducted to show the trends of growing dry beans in the study area for the next ten years under various management practices.

This study considered the two practices discussed above i.e. the farmers' practice and the conservation agriculture practice. In this simulation the CO_2 files from the SRES (Special Report on Emission Scenarios) which are available in the model data subdirectory were used. The files assume different socio-economic storylines. (FAO, 2017)

The simulations were done by creating two projects in the simulation window of AquaCrop. Both projects consisted of 10 successive years specifying the initial conditions and using the calibrated crop file for the area. One of the projects was defined by the farmers current practice while the other was on conservation agriculture. Each of the projects was ran and an assessment on the levels of yield were made.

3.6 Yield gap analysis for dry beans under different treatments in the study area

3.6.1 The Scenarios Applied

In this study the experimental treatments were two; one, dry beans crop grown under the conventional farmers practice in the area that entails soil disturbance before planting by digging and two, crop grown under conservation agriculture, this entails minimal soil disturbances/ zero tillage, application of mulch for moisture conservation and subsequent soil fertility boosting and also entails crop rotation. Each of the treatments was replicated four times in a randomized complete block design with plots measuring 5m by 5m thus a total of eight plots were cultivated. (Ngetich, 2012). The figure below shows the two kind of treatment applied in this study.

Figure 3.5: on the left; Plot under the farmers practice, right plot under Conservation Agriculture (CA)

3.6.2 Yield gap analysis under various scenarios

Aquacrop model was used to determine the potential and attainable yields of crops under different management scenarios. The various simulations conducted in section 3.3.2 resulted in variations in the levels of dry beans yield.

Statistical methods were employed to conduct the gap analysis as discussed in the results chapter.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Measured Crop Yields Obtained

The average yield from the plots under conservation agriculture (CA) practice was 4.5 kg per 5m by 5m plot while that from the plots under farmers' practice was 3.1 kg. This corresponded to 1.8 tons/ ha and 1.2 tons/ha respectively. This was a clear indicator that the plot under CA was able to conserve sufficient levels of moisture thereby the crop suffered no moisture stress at any time in the growth cycle.

4.1.2 Crop development data sheet

Parameter	Date (Year 2018)	Time period (Days)
Crop Planting	4th April	0
90% Emergence	10th April	6 (from planting)
Start of flowering	May 4th	30 (From planting)
Max CC	May 15th	40
End Flowering	May 18th	14 (From start of flowering)
Senescence Start	May 28th	48 (From emergence)
Maturity	June 15th (green mature beans)	66 (From Emergence)
	19th June 2018	72 (From planting)
	20th June (Ready to be harvested but prolonged wet weather)	77 (Ready for harvest)
Harvest	June 27th (Dry grains)	84 (From Planting)

4.1.3 Calibration for cultivar specific parameters

Crop development

The data collected from the field was used in calibrating the various stages of development of the crop as indicated in figure 4.1. This was the calibration for the farmers common practice (without application of the mulch material)

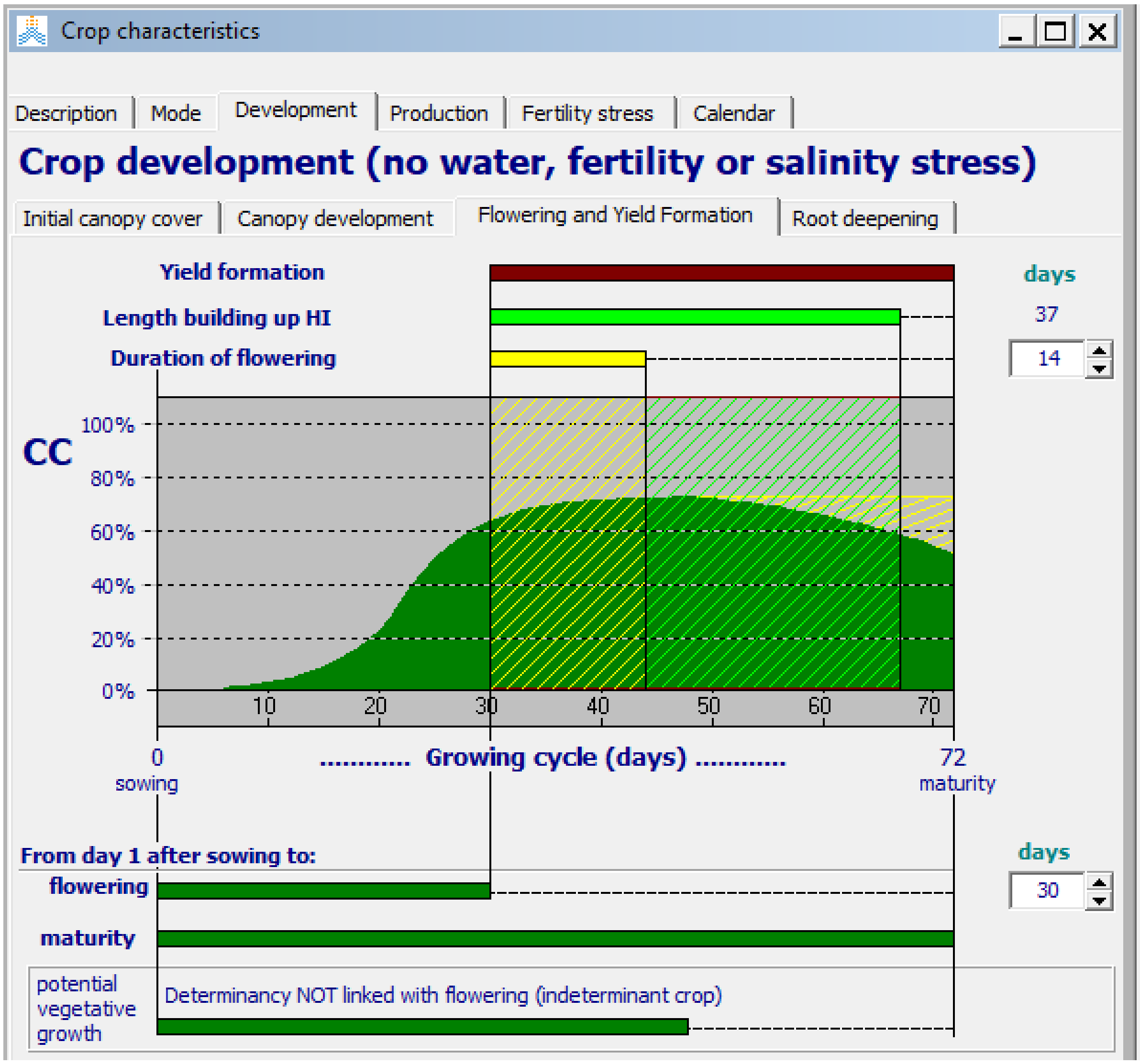

Figure 4.1 Calibration for the various phenological (development) stages of the crop

The crop was planted on the 4th of April 2018 and 90% had emerged on the 6th day after the palnting. The other phenological processes of the crop followed in the days of the season. On the 30th day after planting flowering started and lasted for 14 days. Towards the end of the flowering stage the crop attained the maximum canopy cover of around 75%. The yield formation period kicked off at the onset of flowering lasting for 37 days. The length of building the harvest index was about 68 days. The harvest index is the proportion of biaomass that is the dry grain yield. The crop took a total of 72 days to maturity and was harvested afew days after maturity when the weather conditions were cool and dry to avoid threshing.

Calibration for weed management

The weed management was calibrated as per the weed management on the plot that followed the farmers' practice. The farmers carry bout weeding on week two just before the plant styarts flowering to avoid trampling on the flowers. The plots are again weeded just after the formation of the pods however this depends on the magnmitude of weeds infestration. In figure 4.2 depicts the Relative Cover (RC) of weeds and the corresponding total canopy cover of crop (dark green) and weeds (light green) in the weed infested field and the expected canopy cover for the case of unlimited soil fertility. The RC is at 2% which is the proportion of weeds cover in relation to the total canopy cover. The weeed management mode in the model was defined as very good and towards the mid season there was decrease in the RC amount. These inputs resulted into a model defined figure of 61.3% as the total CC comprising of the crops and the weeds.

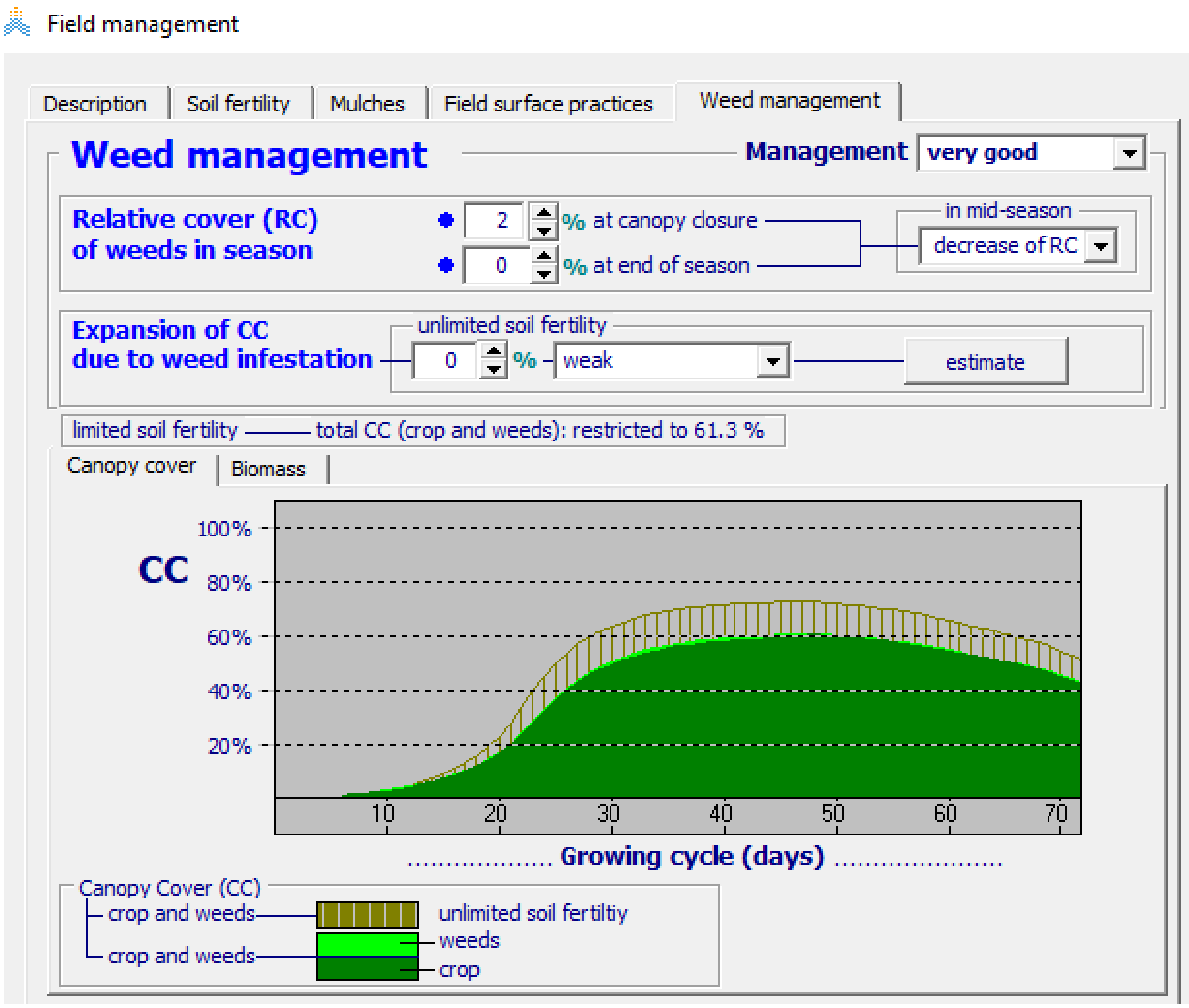

Figure 4.2: Weed management (Crop and weeds combined canopy cover)

Soil Profile Characteristics

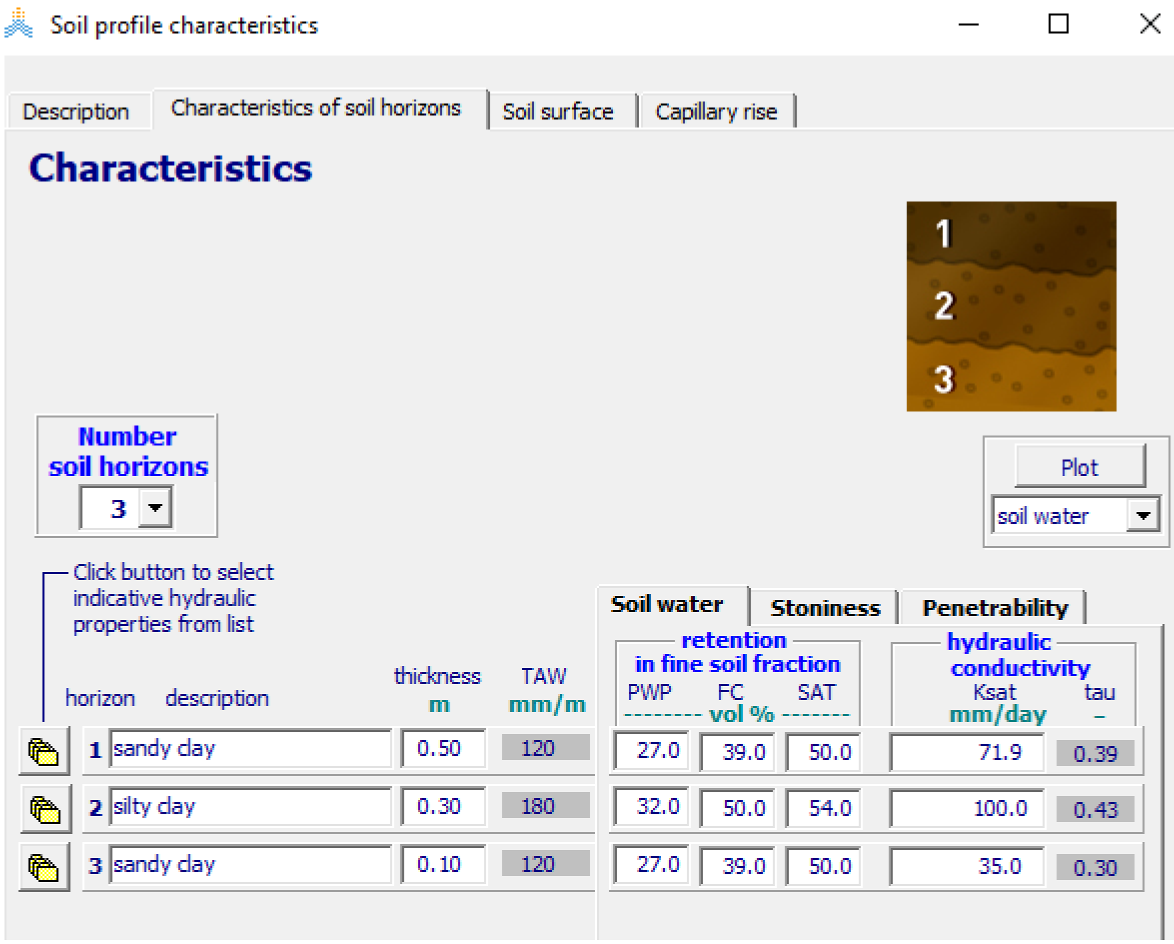

Figure 4.3: Soil profile Calibration results

A. Penetrability

B. Soil Water

ETo Estimation

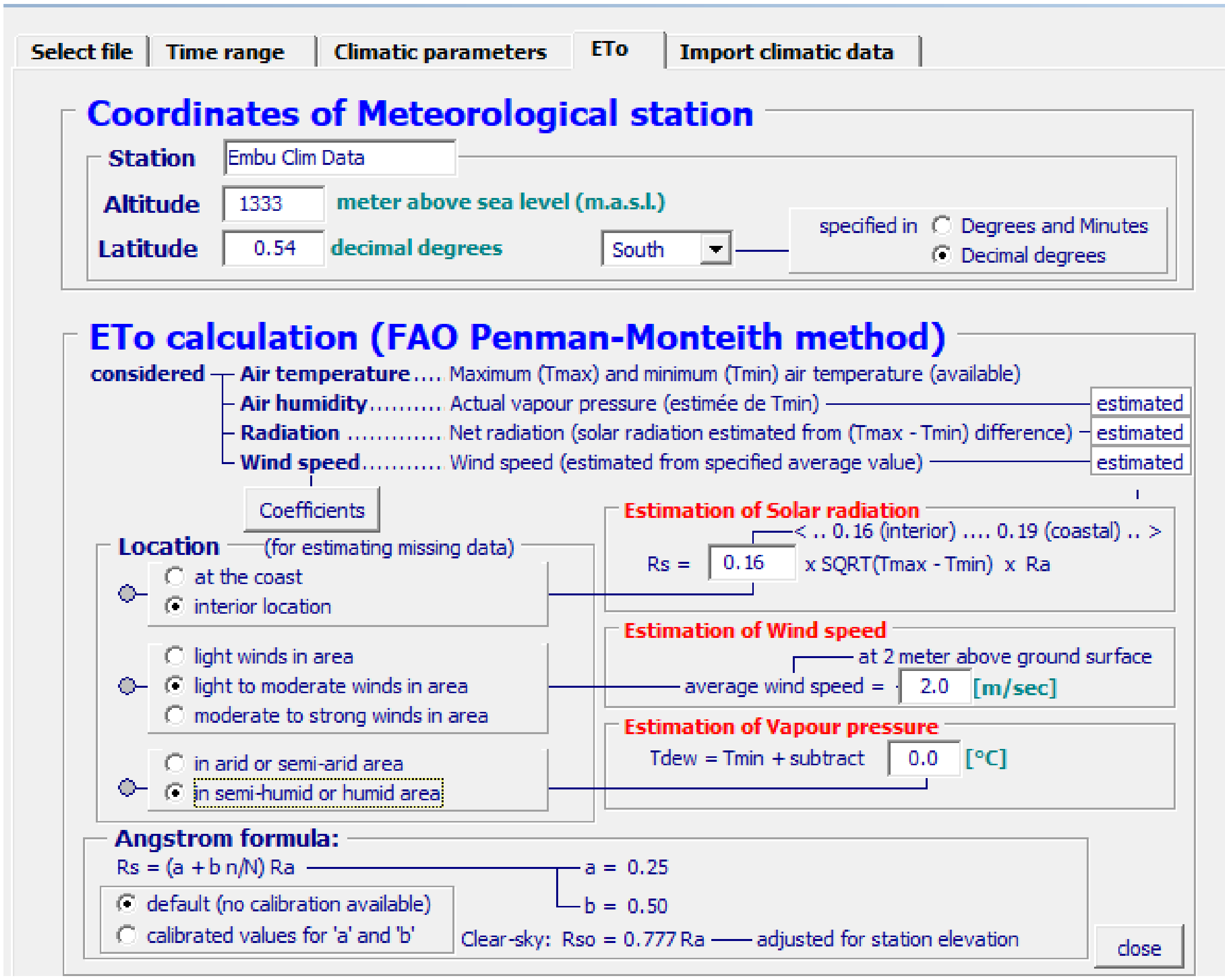

Figure 4.4: Steps in the Estimation of ETo

4.2 Simulations

4.2.1 Farmers' Practice

The first simulation was linked to growing cycle since this done after the calibration of the model

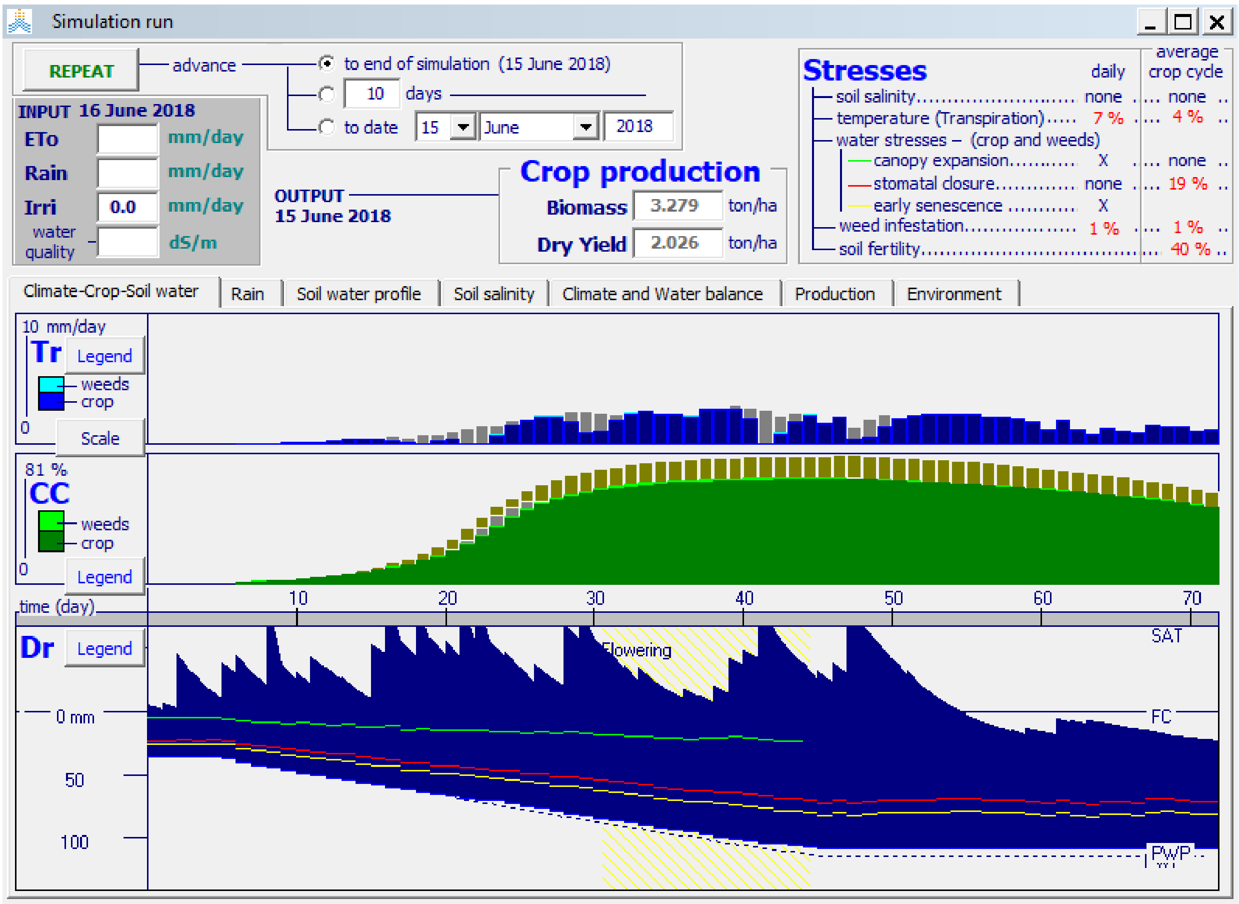

Figure 4.5a: simulation results for the farmers' practice; climate-crop-soil water

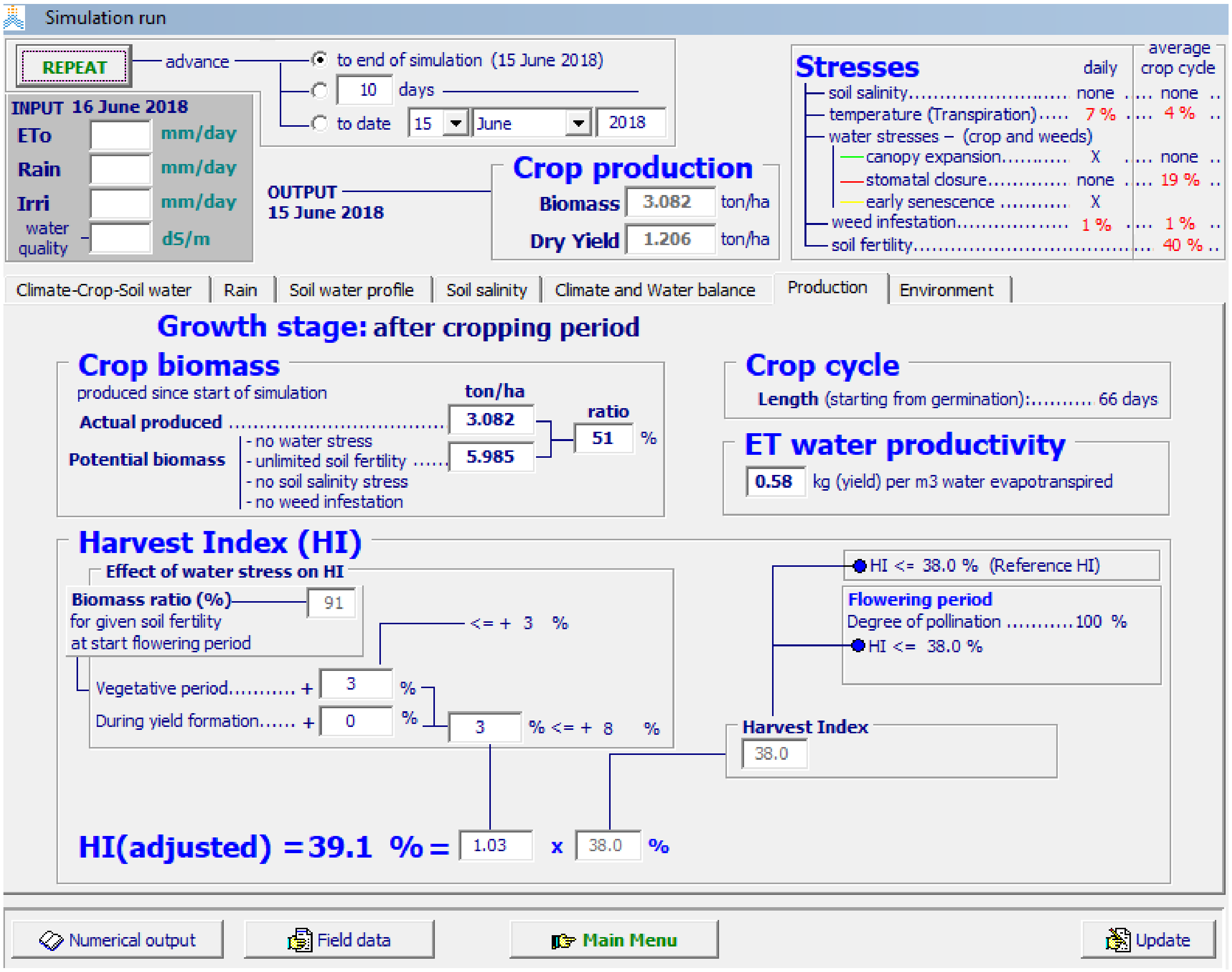

Figure 4.5b: simulation results for the farmers' practice; Crop production results

The dry crop yield for the calibration simulation run was 1.206 ton/ha and a corresponding 3.082 ton/ha biomass production. The observed yield in the field after harvest was 1.2 ton/ha and therefore the difference between the two values was merely 0.006 tons/ha. The harvest index was 39.1% . This is the proportion of the biomass that is converted to dry yileds. The reference harvest index was at 38%. The ET water productivity for this first calibration run was obtained as 0.58kg dry yield per m^3 of water evapotranspired by the crop over the season. This meant that for every $1m^3$ of water evapotranspired a corresspponding yield of 0.58kg was formed. This is an indicator of how well (the efficiency) water was used for the formation of the dry yield. The corresponding biomass water productivity which is a conservative crop parameter for this run was obtained in the environment tab sheet under the crop menu. The value for the biomass productivity was 15.0 g/m^2 which was normalized for climate and CO^2 concentration for the year 2018. The actual biomass produced of 3.082 ton/ha corresponded to a potential biomass production for the area given by the model as 5.985 ton/ha. This meant that the crop biomass was only 51% of the potential biomass production in the area. The highest monthly average level of biomass (2.903 ton/ha) in this simulation was produced in the month of June 2018 and the lowest being 0.105 ton/ha in April. Conservation agriculture heavily relies on biomass production sinbce the biomass produced is usually left in the field to rot increasing the level of organic carbon, nitrogen and other crop nutrients in the soil.

This simulation depicted the typical farmers practice in the study area. Bean crops are grown under the conventional system whereby the soil is usually disturbed using tools such as hoes and forked hoes.

4.2.2 Conservation agriculture simulation scenario

The simulation was conducted by maintaining the calibration parameter values and introducing mulch cover at 25%, 50%, 75% and at 100%. The mulch cover introduced was oraganic in nature and the dry yield level were as **tabulated in table** 4.2.

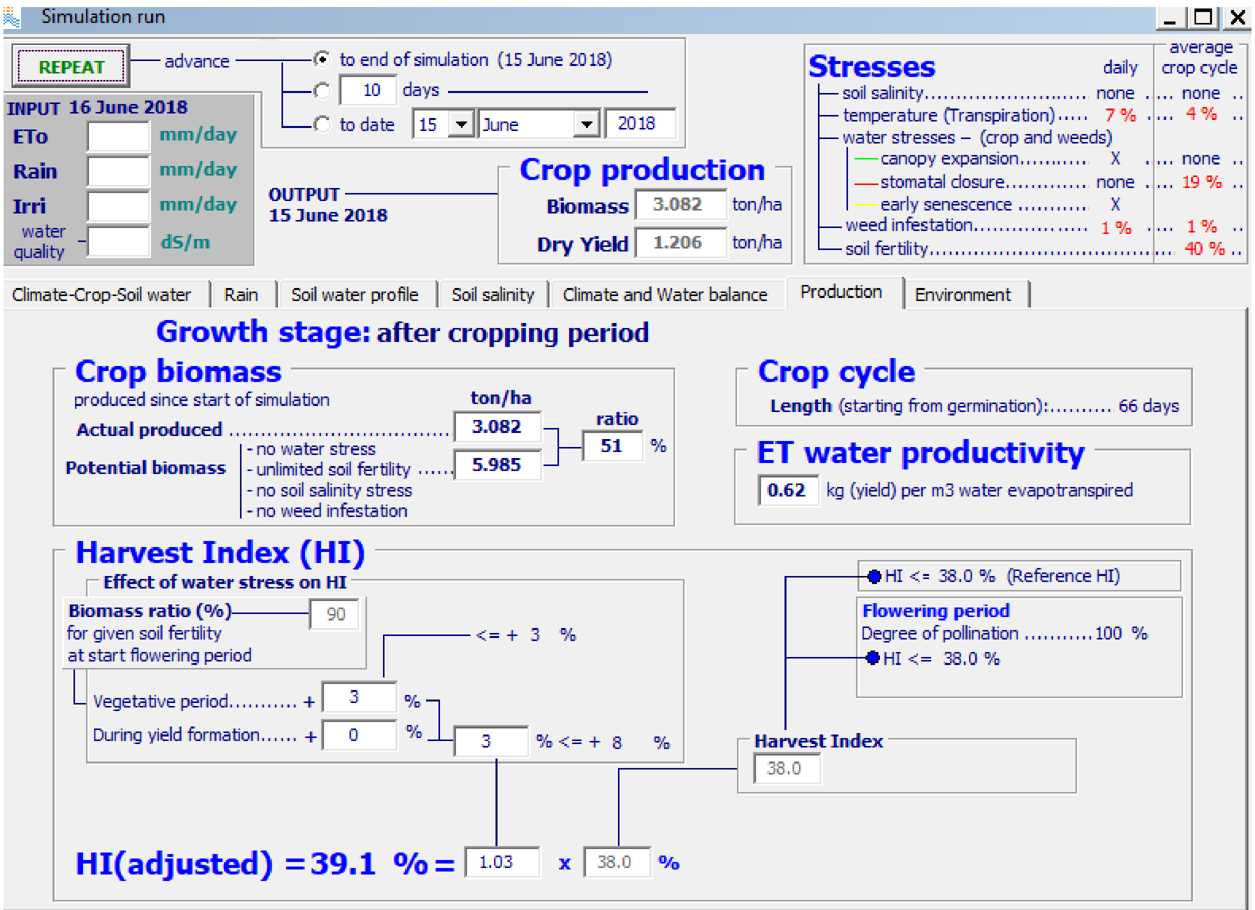

Figure 4. Simulation run results for 25% mulch cover

Table 4.2 Conservation agriculture treatment simulation results

Mulch level (%)	0	25	50	75	100
Biomass (ton/ha)	3.082	3.082	3.082	3.078	3.075
Potential Biomass (ton/ha)	5.985	5.985	5.985	5.985	5.985
Potential/ Actual Biomass Ratio (%)	51	51	51	51	51
Dry yield (ton/ha)	1.206	1.206	1.203	1.197	1.192
Harvest Index (%)	39.1	39.1	39.1	38.9	38.8
Reference Harvest Index (%)	38	38	38	38	38
ET Water Productivity (kg/m^3)	0.58	0.62	0.67	0.73	0.81
Biomass Water Productivity-WP* (g/m^2)	15.0	15.0	15.0	15.0	15.0

Table 4.2 shows biomass generated per unit area under 0%, 25% and at 50% organic mulch application remained constant at 3.082 (ton/ha) however the biomass declined to 3.078 and 3.075 at 75% and 100% levels application respectively. The potential biomass remained unchanged at 5.985ton/ha rendering the potential/actual biomass ratio remain unchanged. The grain yield (dry yield) declined from 1.206 ton/ha obtained at 0% and 25% mulch cover to 1.203, 1.197 and 1.192 at 50%, 75% and at 100% mulch cover respectively. The potential harvest index remained at 38% in all the mulch treatments simulated while the harvest index was constant at 39.1% at 0%, 25% and 50% but declined to 38.9% and 38.8% at &5% and 100% mulch cover.

There is a trend of poor yields obtained with mulch cover above 50%. This could be atttributed to the excess water levels in the soil thereby leading to soil moisture saturation. The excess water makes the soil temparatures low and also causes leaching of plant nutrients leading to low supply. This in return causes poor crop development and lowers the yileds. The mulch cover at 25% appears to be optimal for the area since it leads to an increase in the water productivity from 0.58 for 0% mulch cover to 0.62 besides the two treatments having similar results for all the other parameters evaluated. Organic mulches applied at 25% would therefore be recommended for application on the bean farms in the study area.

Results for the simulation for the future (10) years

This simulation was conducted for both the farmers' practice and the conservation agriculture practice. The simulations were based on an assumption that the farmers would continue with the same system of farming.

CHAPTER FIVE:

CONCLUSIONS, CHALLENGES AND RECOMMENDATIONS

5.1 Conclusions

The AquaCrop model successfully made simulations and accurate predictions for the study area. From the results and discussion chapter

5.2 Challenges faced

Crop failure, this was brought about by excess rains

Conducted only one season crop growing therefore conducting model validation was a challenge

Pests and Diseases attack on the crop

Figure 3.6 Pests and disease attack on the crop

Wet weather conditions during harvesting

Missing data at the Kenya Met station for wind speed and humidity due to faulty equipment

For soil moisture records an onsite moisture meter was too expensive to acquire

5.3 Recommendations

1. Use of a modern weather station at the study site for most accurate weather data collection
2. Aquacrop modelling to be encouraged for planning purposes on crops development in the area, Kenya, region and Africa at large
3. Improving farm management strategies through AquaCrop
4. The model is an effective tool in aiding the development of water management strategies to improve crop production and save water. This could therefore be applied to recommend crop management practices in the dry areas experiencing crop moisture stress
5. Planning and scenario analysis could further be done by users such as agricultural extension workers and specialists, water managers, personnel of irrigation organisations, economists and policy specialist especially by use of the AquaCrop plug in tools such as the Economic tools

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APPENDICES

1. Crop Growing photos

Mid-Season and Crop harvesting Images




2. Soil Lab Analysis Reports

Kenya Agricultural & Livestock Research Organization
National Agricultural Research Laboratories
Soil Physics Laboratory
Tel: 254 20 2464435
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Date: 7th August, 2018

Charles M. Gichovi
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Embu

RE: DRY SEIVING, POROSITY, BULK DENSITY, HYDRAULIC CONDUCTIVITY ANALYSES

Attached please find the results of the above mentioned analyses for one soil sample Lab. No. 2086, 2088, 2100, 2101/2018 (Ref: Hinga G., F. N. Muchena and C. M. Njihia, 1980: Physical and chemical methods of analysis).

Thank you for using our services.

I. V. Sijali
COORDINATOR IRRIGATION, DRAINAGE AND PROBLEM SOILS RESEARCH PROGRAMME

DRY SEIVING

Lab. No./2018	% Soil Particles Retained at Sieve Opening Size (mm)							
	3	**2**	**1**	**0.5**	**0.25**	**0.15**	**0.075**	**< 0.075**
2086	14.59	14.43	30.22	28.00	7.65	4.63	0.028	0.32

SOIL POROSITY

Sample Description	Lab. No./2018	% Porosity
Top	2088	50.6

SOIL BULK DENSITY

Sample Description	Lab. No./2018	Bulk Density (g. cm^{-3})
Top	2100	1.3

HYDRAULIC CONDUCTIVITY

Sample Description	Lab. No./2018	Hydraulic Conductivity cm/hr.
Top	2101	7.19

Crop Growing photos

Mid-Season and Crop harvesting Images

Clockwise from Top: Bean Crop Few days after germination, At flowering stage, at pod formation stage and the final image is during harvesting