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Modelling the Impact of Biochar and Fertilizer on Maize Production in Kenya Using the FAO AquaCrop Model

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Now it is time to leave on a high note, and step out of the Ås-bubble to take on new adventures.

Mathilde Brunvoll

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Abstract

Sub-Saharan Africa is facing a number of challenges due to climate change, that all affect food security. There is an urgent need for sustainable solutions that can help increase crop production and support resilient agricultural systems. This thesis explores the impact of applying biochar in combination with mineral fertilizer on maize production in Embu, Kenya, using the crop growth model AquaCrop, developed by the United Nation's FAO. As part of the BICEPS project, the study investigates whether this integrated soil amendment strategy can enhance crop productivity and increase resilience to climate-related stress as a conservation agriculture (CA) practice. The study found that added nutrients (from fertilizer) were the primary driver of yield improvements, rather than biochar's effect on soil water retention. Two treatments were analyzed: one with 3 tons of biochar per hectare and fertilizer (BC3F), and a control with no inputs. Field data were collected and used to calibrate simulations in AquaCrop to evaluate yield development, soil water balance, and the effects of sowing date variation.

The model, after calibration, reproduced observed biomass values for both treatments. The BC3F simulated significantly higher biomass (7.48 t/ha) and grain yield (3.26 t/ha) compared to the Control (2.60 t/ha and 1.15 t/ha), underlining the importance of nutrient supply. This matched very closely with the observed biomass of 7.27 ton/ha for BC3F and 2.37 for the Control. However, the model had difficulty reproducing observed canopy cover, especially under stressed conditions. This was likely due to AquaCrop's simplified fertility stress approach and potentially a mis-match between field-measured canopy cover and the internal definition in AquaCrop. Statistical analysis of the soil water retention data showed no significant difference between treatments, indicating that biochar had no measurable effect on water-holding capacity in this experiment. The lack of a biochar-only treatment limited the ability to isolate biochar's independent effect on yield. A hypothetical AquaCrop simulation without fertilizer inputs was attempted to explore this scenario, but the model could not produce realistic results due to calibration challenges and the absence of observed data for validation. Simulation of alternative sowing dates indicated that earlier planting may improve yield and reduce water stress during the 2024 season's weather.

These results suggest that agronomic management strategies such as integrated nutrient use and sowing date adjustments could enhance maize performance in smallholder systems. Nonetheless, the simulations also revealed AquaCrop's limitations in fully capturing biochar-soil-plant interactions, particularly under nutrient stress. In conclusion, while biochar alone did not improve soil water retention, its combination with fertilizer proved effective for yield enhancement. These findings support that boosting nutrient availability is key to increase maize production, supporting the use of integrated soil fertility management in climate-resilient maize production. Future work should include more detailed nutrient modeling, multi-year field validation, and scenario-based AquaCrop simulations to explore biochar's effects under varying input conditions, in order to better assess its role in sustainable intensification strategies in sub-Saharan Africa.

Sammendrag

Afrika sør for Sahara står overfor en rekke utfordringer knyttet til klimaendringer, som alle påvirker matsikkerheten. Det er et akutt behov for bærekraftige løsninger som kan bidra til å øke matproduksjonen og styrke robustheten i landbrukssystemene. Denne oppgaven undersøker effekten av å bruke biokull i kombinasjon med mineralgjødsel på maisproduksjon i Embu, Kenya, ved bruk av vekstmodellen AquaCrop, utviklet av FNs organisasjon for ernæring og landbruk (FAO). Som en del av BICEPS-prosjektet undersøker studien om denne integrerte strategien for jordforbedring kan øke avlingsnivået og motstandskraften mot klimarelaterte stressfaktorer, innenfor rammen av bevaringsjordbruk (CA). Studien fant at det var næringstilførselen (fra gjødsel) som var hoveddriveren bak økt avling, snarere enn biokullets effekt på jordas vannlagringsevne. To behandlinger ble analysert: én med 3 tonn biokull per hektar og gjødsel (BC3F), og en kontroll uten noen tilførsel. Feltdata ble samlet inn og deretter brukt til å kalibrere simuleringer i AquaCrop for å vurdere avlingsutvikling, vannbalanse i jorda og effekten av endret såtid.

Modellen, etter kalibrering, klarte å gjenskape observert biomasse for begge behandlinger. BC3F-simuleringen viste betydelig høyere biomasse (7,48 t/ha) og kornavling (3,26 t/ha) sammenlignet med kontrollen (2,60 t/ha og 1,15 t/ha), noe som understreker viktigheten av næringstilgang. Disse resultatene samsvarte tett med observert biomasse på henholdsvis 7,27 t/ha for BC3F og 2,37 t/ha for kontrollen. Modellen hadde imidlertid utfordringer med å reprodusere observerte verdier for bladdekke, særlig under næringsstress. Dette skyldes trolig AquaCrops forenklede tilnærming til fertilitetsstress og mulig avvik mellom feltmålt bladdekke og modellens interne definisjon. Statistiske analyser av jordas vannretensjon viste ingen signifikante forskjeller mellom behandlingene, noe som indikerer at biokull ikke hadde noen målbar effekt på jordas vannlagringsevne i dette forsøket. Mangelen på en ren biokull-behandling gjorde det vanskelig å isolere biokullets uavhengige effekt på avling. En hypotetisk AquaCrop-simulering uten gjødsel ble forsøkt for å undersøke dette, men modellen klarte ikke å generere realistiske resultater på grunn av kalibreringsutfordringer og fravær av feltdata til validering. Simuleringer med alternative sådatoer viste at tidligere såing kunne forbedre avling og redusere vannstress under vekstsesongen 2024.

Disse resultatene tyder på at agronomiske tiltak som integrert næringsbruk og tilpasning av såtid kan bidra til bedre maisproduksjon i småskala systemer. Samtidig viste simuleringene begrensninger ved AquaCrop-modellen når det gjelder å fange opp interaksjoner mellom biokull, jord og planter, særlig under næringsmangel. Oppsummert viste studien at biokull alene ikke forbedret jordas vannretensjon, men at kombinasjonen med gjødsel hadde en positiv effekt på avlingene. Funnene understøtter at forbedret næringstilgang er avgjørende for å øke maisproduksjonen, og støtter bruken av integrert jordfruktbarhetsforvaltning som en strategi for klimarobust landbruk. Fremtidig forskning bør inkludere mer detaljert modellering av næringsstoffer, flerårig feltvalidering og scenario-baserte AquaCrop-simuleringer for å undersøke biokullets effekt under ulike innsatsnivå, for å kunne vurdere dets rolle som bærekraftig landbruksstrategi i Afrika sør for Sahara.

List of Abbreviations

SSA: Sub-Saharan Africa
CA: Conservational agriculture
WP: Water productivity(WP* normalized for CO_2) as input parameter in AquaCrop
Kast: Saturated hydraulic conductivity
SAT: Saturation
FC: Field capacity
PWP: Permanent wilting point
TAW: Total available water
FAO: Food and Agriculture Organization
CC: Canopy cover

List of Figures

List of Tables

Table of Contents

Chapter 1: Introduction

This chapter presents the background for the master's thesis, which is based on challenges related to food production in Sub-Saharan Africa. It includes an introduction to biochar production and a review of previous studies on the use of biochar, highlighting its advantages and disadvantages. In addition, the chapter discusses how modeling tools such as AquaCrop can be useful for crop yield prediction.

1.1 Project Description

The thesis is written as a part of the project BICEPS - Biochar Integration in Small-Holder Cropping Systems – Economy, Food Product Value Chains, Climate Change Resilience and Soil Fertility, supported by the European Union. The BICEPS project aims to assess the contribution of biochar to agriculture and food production and climate resilience (Foscera, 2025). It also intends to improve food security and profitability in small-holder agriculture and address remaining knowledge gaps in biochar-crop-soil interactions. The thesis focuses on crop production with biochar addition in a climate smart agricultural perspective. By using data and parameters connected to climate, crop and soil characteristics, the United Nations Food and Agriculture Organization's AquaCrop model is used for predictions and modeling. The thesis focuses on one of the sites from the project, Embu, located in Kenya and is investigating selected treatments from this experiment.

1.2 Objective of the Study

This study investigates the effect of biochar in combination with mineral fertilizer on maize production in Embu, Kenya, as part of a conservation agriculture approach without crop rotation. The FAO AquaCrop model was calibrated using measured field data and applied to simulate different sowing date scenarios. The analysis compares canopy development, soil water retention, and biomass and yield production for two treatments: 3 tons per hectare of biochar with fertilizer, and a control without biochar or fertilizer. The following research questions are addressed:

1. Can the AquaCrop model reproduce the observed field data through calibration?
2. What is the effect of biochar combined with mineral fertilizer on maize growth and yield?
3. How does biochar effect soil properties?
4. How does altering the sowing date affect simulated biomass and yield?

1.3 Background Information

1.3.1 Food Security in Sub-Saharan Africa

The Food and Agriculture Organization (FAO) has found that world hunger has risen over the last years, and in 2021 hunger affected 278 million people in Africa (FAO et al., 2022). Sub-Saharan Africa is facing a number of challenges due to climate change, such as drought, flood and extreme heat – that all effect food security. The continent of Africa faces disproportionately high expenses for necessary climate adaptation, according to the World Meteorological Organization (World Meterological Organization, 2023). Additionally, soil degradation is a major problem in sub-Saharan Africa, and the effects may be most profound in developing nations where a significant portion of the population relies directly on agriculture for their livelihood (Tully et al., 2015). Approximately 65% of agricultural land is degraded, primarily due to inadequate nutrient application, soil erosion, and soil acidification (Zingore et al., 2015).

Another significant challenge faced by the farmers in the sub-Saharan region is water scarcity and a limited input of chemical fertilizers (Kisaka et al., 2015). Kenya, situated in East Africa is one among many countries grappling with these issues. The drier regions of Kenya's central highlands and eastern areas continue to face unpredictable rainfall patterns, frequent dry spells, and droughts, accompanied by high evapotranspiration rates (Kisaka et al., 2015). Although the total annual rainfall is generally sufficient, its distribution is highly uneven, with about 25% of the annual rainfall occurring in just a few intense rainstorms. This poor temporal distribution leads to water stress for crops, often resulting in complete crop failure (Kisaka et al., 2015). The soil cannot retain all the water from the rainfall, so improving soil water retention is necessary to tackle these issues (Rawls et al., 2003).

Many soils in sub-Saharan Africa (SSA) are in poor condition, mainly because nutrients have been depleted over time through farming, without being sufficiently replaced by fertilizers or organic matter (Jones et al., 2013). Mineral fertilizers represent one of the most effective tools for reversing soil nutrient depletion in sub-Saharan Africa (Bationo et al., 2007). However, the annual cost of nutrient mining is considered very high. While overuse of fertilizers and manure has led to environmental degradation in many high-income countries, the opposite challenge exists in SSA - insufficient fertilizer use is a key contributor to soil degradation and declining land productivity, ultimately undermining both environmental sustainability and rural livelihoods (Bationo et al., 2007). Given the combination of low soil fertility and the high cost of fertilizers, there is an urgent need for effective and sustainable solutions. Studies also suggest that increasing fertilizer inputs alone could substantially narrow the yield gap in SSA, even without the introduction of irrigation (Mueller et al., 2012).

The need for improved food security in SSA is increasing. This thesis will investigate one possible management solution: the use of biochar in agriculture in combination with mineral fertilizer. Biochar has the potential to improve soil structure and fertility, enhance water retention, and reduce nutrient loss – which are all key challenges in the region (Bationo et al., 2007; Jones et al., 2013; Kisaka et al., 2015). The study will assess these effects through field data and modeling to evaluate the role of biochar in sustainable land management.

1.3.2 Conservation Agriculture

Conventional agricultural methods in sub-Saharan Africa, like extensive and frequent tillage, total removal of crop residue, and biomass burning, pose threats to soil integrity by degrading the soil (Meshesha et al., 2024). In response to these threats, approaches that today are popularly termed as "conservation agriculture" (CA) practices can be implemented. These approaches, which often include minimal soil interference, keeping crop residue, and crop rotation, aim to lessen soil erosion, enhance soil quality and crop yield, and aid in climate change mitigation and adaptation (Meshesha et al., 2024). However, in the field from this study's experiment, it was only minimum tillage and residue retention that were implemented. One of the approaches to restore soil fertility is the use of soil amendments, among them e.g. biochar. Soils in smallholder cropping systems in these areas are often nutrient-poor, with low pH, organic matter, and water-holding capacity, which often makes these soils highly responsive to amendments like biochar (Gwenzi et al., 2015).

1.3.3 Maize Production

Maize (*Zea mays L.*) is the most extensively grown crop in SSA and plays a crucial role in food security and livelihood in the region (Ten Berge et al., 2019). It contributes significantly to food security, providing a high percentage of the caloric intake for low-income households (Abate et al., 2017). Maize is one of the top cereals in many countries in SSA and is grown on over 40M ha in this region (Cairns et al., 2021). However, maize production faces significant challenges, including climate variability, drought, pests such as the fall armyworm (*Spodoptera frugiperda*), and post-harvest losses due to inadequate storage facilities (Prasanna et al., 2018). Despite these obstacles, maize remains a crucial component of economic stability and rural development in Sub-Saharan Africa (AGRA, 2019)

1.3.4 Biochar

Biochar, which is a carbon-rich substance, is created through the pyrolysis of organic biomass (Schmidt et al., 2021). Pyrolysis can be defined as the thermal decomposition of organic materials in the absence of oxygen (Demirbas & Arin, 2002). Often referred to as a "soil conditioner," biochar plays a vital role in improving soil quality. While a wide range of materials can be used as biomass feedstock, such as wood, crop residues, and animal manures, the effectiveness of each feedstock depends on various factors. These include not only the chemical and physical properties of the material but also environmental considerations, alongside economic and logistical feasibility (Verheijen et al., 2010).

The use of biochar could potentially improve soil and crop productivity by increasing nutrient availability, enhancing soil moisture retention, and neutralizing acidic soils (Schmidt et al. 2021). It also promotes microbial diversity and activity, creating a healthier and more resilient soil ecosystem that supports sustained agricultural growth (Gwenzi et al., 2015). Literature on the agronomic impacts of biochar show enhanced soil fertility and crop productivity, especially where biochar was combined with fertilizers (Gwenzi et al., 2015).

1.3.4.1 Production of Biochar

The biochar used in this study is made according to the Kon Tiki method, also referred to as the flame curtain pyrolysis method. This process involves burning biomass layer by layer in a kiln or a pit. A fire is started, a layer of biomass is added, and it begins to pyrolyze (Figure 1). The resulting pyrolysis gas ignites, forming a 'flame curtain' that shields the biochar below from oxygen, preventing it from burning up. The process is repeated until the kiln is full, and then stopped by quenching with water or a nutrient solution, or by covering with soil. The temperature in the main pyrolysis zone ranges from 680°C to 750°C, cooling down when new layers are added (Cornelissen et al., 2016).

Figure 1. Open flame Kon Tiki method of biochar pyrolysis in Gulu, Uganda. Photos: Mathilde Brunvoll

This production system is simple to construct and can be effectively utilized by farmers in both developed and developing regions. Biochar produced from various feedstocks meets international quality standards, such as those set by the European Biochar Certificate and the International

Biochar Initiative. Furthermore, gas and aerosol emissions are significantly lower compared to other low-cost or traditional methods of charcoal and biochar production (Cornelissen et al., 2016).

1.3.4.2 Feedstock

Crop waste can be used to produce biochar with feedstocks like maize cobs, wheat straw, rice straw, soybeans and potatoes (Ippolito et al., 2020). The physico-chemical properties of biochar, including surface area, pH, and concentrations of elements such as carbon (C), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca), vary depending on the feedstock and the production temperature. These factors influence biochar's performance and its effects on soil properties, making them critical considerations in its application (Gul et al., 2015). There is however limited knowledge about this, and there is a strong need to fill such knowledge gaps (Li et al., 2019).

Maize cobs are a great feedstock for production of biochar, as it is a significant agricultural residue and contributes to solid waste globally (Assirey & Altamimi, 2021). The biochar can have highly adsorptive properties which can be beneficial for the soil (Assirey & Altamimi, 2021). Maize cob biochar typically exhibits an increase in pH with higher production temperatures, while the total nitrogen content decreases (Eduah et al., 2019). Other studies support that increasing the pyrolysis temperature generally leads to higher biochar pH levels and a decrease in total nitrogen content. These changes can significantly influence the biochar's impact on soil properties, including soil acidity and nutrient availability (Khater et al., 2024).

1.3.4.3 Positive Effects of Biochar

Studies show that biochar can alter physical and chemical soil properties such as pH, nutrient content and plant available water (Schmidt et al., 2021). Particularly the porous structure of biochar has been shown to have a number of positive effects on the total porosity (Yang et al., 2022). According to a study about the long-term effects of biochar on agricultural soils, application of 3% by weight of the soil decreased bulk density, improved soil aggregate stability and improved plant available water (Burrell et al., 2016). Increased microbial activity has also been shown as a result of biochar use when biochar made of rice straw was applied to Utisols, which are highly acidic and weathered (Yang et al., 2022). Another study from SSA by (Geng et al., 2022) also found that using biochar raised the soil's pH, decreased its exchangeable acidity, and mitigated aluminum's harmful effects. Additionally, biochar enhanced the levels of Potassium (K), Sodium (Na), Calcium (Ca), and Magnesium (Mg) in the soil. Biochar possesses a high cation exchange capacity, which could help reduce the leaching of cationic nutrients when incorporated into the soil (Geng et al., 2022).

Biochar also confers additional beneficial effects beyond soil-related properties, which are noteworthy and should be taken into account. Studies show that biochar shows strong potential for CO2 sequestration and GHG reduction in Sub-Saharan Africa (Gwenzi et al., 2015). African soils, just like other soils, hold a significant carbon stock, and biochar, with its stable carbon content, can lock carbon in soils for centuries. It can reduce CO_2, CH_4, and N_2O emissions, supporting global climate targets and improving soil health. Globally, biochar could offset 1–2 billion tons of CO_2

annually, but its impact depends on soil type and management practices. Despite some variability in results, biochar remains a promising tool for sustainable agriculture and climate mitigation (Gwenzi et al., 2015).

A four-season study on smallholder farms in Kenya found consistent increases in maize yields from applying biochar at realistic rates (1, 5, and 10 ton/ha), with average yield gains of 1.0, 2.6, and 4.0 ton/ha, respectively (Kätterer et al., 2022). Yield improvements were observed regardless of baseline soil fertility, site, season, or biochar feedstock, though slightly stronger effects occurred where nutrient-rich biochar was used. The biochar was applied in planting furrows, concentrating it in the crop root zone. The findings suggest that low-rate, wide-area biochar application is more efficient than high-rate, small-area use (Kätterer et al., 2022). High application rates may not be practical or economical (Atkinson, 2018). Biochar from agricultural waste offers a sustainable strategy to boost food production and mitigate climate change in rural Kenya (Kätterer et al., 2022).

1.3.4.4 Biochar and Soil Water Retention

A meta-analysis by (Razzaghi et al., 2020) that investigated the effect of biochar addition on soil water retention concluded that biochar generally reduced soil bulk density and increases plant available water. While it increased water retention in coarse- and medium-textured soils, it decreased it in fine-textured soils, indicating a soil type-dependent effect (Razzaghi et al., 2020). Other studies investigated the importance of the amount of biochar applied and the effect of their particle size on its potential benefits (Tanure et al., 2019). Biochar with different particle sizes had similar effects on plant growth and soil quality. Particle size influenced soil properties only when directly related to the variable measured, like bulk density (large particles) and microporosity (small particles). Although biochar improved water retention, it was not enough to alleviate drought stress. High application rates enhanced soil fertility, plant nutrition, and growth (Tanure et al., 2019). When properly mixed and applied, the soil amendment can enhance soil stability and promote plant growth (Kang et al., 2022).

Although numerous studies report that biochar can enhance soil properties, particularly soil water retention, its effectiveness is highly dependent on soil type. A study published by (Mannan et al., 2021) found that biochar application did not improve plant water availability in clay soils. The research suggested that any observed improvements in plant performance were likely due to enhanced nutrient supply rather than increased water uptake (Mannan et al., 2021). A multi-year study from Utah investigated the effects of biochar use in maize production (Holt et al., 2022). They found no consistent effects of biochar on crop yield, quality, or soil water availability. Given its high cost and lack of short-term agronomic benefits, biochar was not considered economically viable without subsidies in this region (Holt et al., 2022). Although the latter study cannot be directly applied to conditions in sub-Saharan Africa, it remains important to weigh the advantages and disadvantages of biochar use when evaluating its overall effectiveness.

1.3.5 Risks and Limitations to Use of Biochar

1.3.5.1 Cost of Labor and Farmers Perceptions

While biochar exhibits numerous positive effects on crop yields and could be a potential poverty alleviation, it also entails certain socioeconomic considerations, one of which is the labor cost associated with its production. A study from 2021 looked into the environmental and economic impacts of biochar production and agricultural use in developing countries (Owsianiak et al., 2021). It showed that the African countries in the study have relatively high profitability as the value of the increase in maize production compensates for their low labor costs. The research also shows that it is not as profitable in countries with higher labor costs (Owsianiak et al., 2021). Another study conducted on hedgerow intercropping, investigated farmers willingness to provide land for experiments. It indicated that while trial farmers acknowledge the potential of hedgerow intercropping to enhance crop yields, mitigate erosion, and supply firewood, the majority did not perceive the long-term benefits to outweigh the short-term risks, such as diminished crop productivity, and the additional labor required (David, 1995). Critics of biochar and its co-products argue that sourcing biomass feedstock can contribute to habitat degradation, biodiversity loss, and the diversion of crop residues from soils, potentially undermining soil health and ecological sustainability (Gwenzi et al., 2015). Undeniably, the utilization of biochar encounters issues that extend beyond its direct influence on crop outcomes. The farmers socioeconomic perspective therefore needs to be taken into consideration when discussing the increased use of biochar for smallholder farmers. Biochar remains a relatively unfamiliar technology for most smallholder farmers. Successful implementation of new biochar initiatives in rural areas will require a context-specific understanding of local communities with their needs, values, and expectations (Seitz & Solomon, 2016).

1.3.5.2 Lack of Knowledge

Biochar faces various challenges, including policy, legal, financial, and socio-economic issues. In sub-Saharan Africa, the adoption of new technologies like biochar depends on supportive laws and policies, which often stem from the benefits of the technology. However, many governments in this region may not be aware of biochar, leading to a lack of clear rules or policies for it. As a result, traditional technologies are often prioritized over biochar. This is different from developed countries where large biochar production plants already exist (Gwenzi et al., 2015).

1.3.5.3 Availability of Biomass to Biochar Production

An important question that needs to be raised while discussing the potential production of biochar, is the availability of biomass as feedstock for smallholder farmers. Feedstock costs vary greatly due to differences in maize yields, planting density, and how much farmers value maize residues (Berazneva et al., 2021). The integration of biochar into cropping systems should rely on genuine waste materials with no competing uses; otherwise, it risks undermining food security, particularly in vulnerable regions like sub-Saharan Africa. If not managed carefully, biochar initiatives could contribute to land grabbing, deforestation, and biodiversity loss (Seitz & Solomon, 2016). This highlights the importance of carefully considering biomass availability when evaluating the feasibility of biochar systems.

1.3.6 Simulation and Crop Growth Modelling

A scientific model is a simplified representation of a real-world system used to understand, explain, or predict how it works. Models can be physical, mathematical, or computational and help scientists test ideas without observing the actual system directly (Frigg & Hartmann, 2006). Modeling and simulation serve as valuable tools for planning, designing, and evaluating dynamic systems, as well as assessing strategies for system transformation and change (Birta & Arbez, 2013). Crop modeling is a valuable tool for simulating plant growth, assessing environmental impacts, and optimizing management practices to improve agricultural productivity and sustainability (Jones et al., 2017). These models integrate data on climate, soil, and crop traits to support decision-making in precision agriculture and climate adaptation strategies (Boote et al., 2013).

1.3.6.1 The FAO AquaCrop Model

An example of a well-developed model that is excellent for crop growth simulations is the AquaCrop model, developed and promoted by United Nations Food and Agriculture Organization. AquaCrop uses a limited set of conservative crop parameters to simulate final yield through four clear steps, making the modeling approach transparent and easy to understand (Vanuytrecht et al., 2014). This model aimes at improving food security and evaluating how environmental conditions and management practices impact crop yields. Designed specifically for herbaceous crops, the model simulates yield responses to water availability, making it particularly valuable in regions where water is a primary limiting factor. The model is crafted to maintain a balance between ease of use, precision, and reliability. It achieves this by relying on a small set of clearly defined parameters and intuitive input variables that are simple to assess. Despite its simplicity, AquaCrop is rooted in detailed biophysical processes, ensuring that it accurately represents the interactions between crops and the plant-soil system(FAO, 2025b).

Figure 2 visualizes how the AquaCrop model works by showing the relationship between various input factors and the model's outputs. The model takes several types of input, including weather data (such as rainfall, temperature, and solar radiation), crop characteristics, soil profile, groundwater conditions, and different management practices like field and irrigation management. These inputs are used to simulate plant growth and responses to environmental factors. The output from the model includes biomass production and crop yield under specific environmental conditions. A key result of the model is water productivity, expressed as WP_{ET} (Water Productivity of Evapotranspiration), which measures how many kilograms of yield are produced per cubic meter of water evapotranspired by the crop during the growing season. This makes AquaCrop a valuable tool for assessing sustainable water use in agriculture.

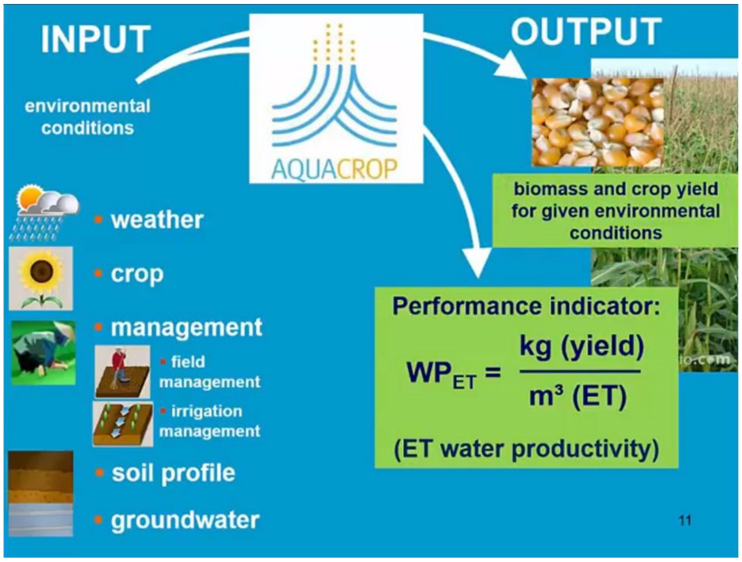

Figure 2. Input and output data for the AquaCrop model (FAO, 2016).

The AquaCrop model has been widely applied to simulate yield responses for various crops, including maize (Greaves & Wang, 2016). It has been shown that AquaCrop performs well in modeling maize development, grain yield, and water-related variables such as evapotranspiration (ETc) and water use efficiency under non-limiting conditions. However, its performance tends to decline in estimating certain variables, like senescence of canopy, under severe water stress (Hsiao et al., 2009). Researchers highlight the need to calibrate key factors, including climate, soil, crop cultivars, irrigation practices, and field management, to enhance the model's accuracy and reliability across varied scenarios. Testing and calibrating these parameters under different conditions is crucial to improving the precision of simulation results (Greaves & Wang, 2016).

To justify the use of AquaCrop for simulating maize growth, the benchmark criteria proposed by (Saloranta et al., 2003) offer a valuable framework for selecting appropriate models in water management and agricultural planning. These criteria emphasize aspects such as data requirements, user-friendliness, model complexity, and applicability in real-world decision-making contexts (Saloranta et al., 2003). AquaCrop performs well across several of these dimensions. It requires relatively limited input data, making it suitable for use in data-scarce regions, particularly in sub-Saharan Africa. Furthermore, its strong focus on simulating yield response to water aligns well with the needs of climate-smart agriculture and resource-efficient crop production and its modeling. The model is also supported by extensive documentation and has been validated in a wide range of agroecological zones, which enhances its credibility and transferability. Using the model selection framework developed by (Saloranta et al., 2003) thus supports the conclusion that AquaCrop is a practical and scientifically sound tool for modeling maize crop growth under varying environmental conditions.

1.3.6.2 Required Parameters

Crop parameters define the physiological and phenological characteristics of a specific crop, including its canopy development, water productivity, rooting depth, and sensitivity to water stress. These parameters are crucial in simulating biomass accumulation and yield formation. For instance, crops differ in their transpiration efficiency, which influences how efficiently they convert water into biomass (Steduto et al., 2009). Additionally, parameters such as flowering time, harvest index, and maximum canopy cover impact the final yield estimation.

Climate parameters describe the environmental conditions that influence crop growth, including temperature, rainfall, solar radiation, relative humidity, and wind speed. These factors determine the rate of evapotranspiration. AquaCrop relies on daily or monthly weather data to simulate how crops respond to varying climatic conditions. Temperature affects phenological development, while precipitation and evapotranspiration govern soil water balance and irrigation requirements (Raes et al., 2009).

Soil parameters influence water movement and storage within the root zone. Key soil properties include texture, field capacity, wilting point, and saturated hydraulic conductivity, which determine water retention and the soil's infiltration and drainage capacity. The soil profile is divided into layers, each with specific characteristics affecting water infiltration and root penetration. These parameters are essential in modeling soil water balance and ensuring realistic crop responses to water availability (Heng et al., 2009).

1.3.6.3 Studies on Biochar using AquaCrop

Using the AquaCrop model, a study from South Sudan simulated the impact of biochar on sorghum biomass and grain yield, applying typical field doses (Starr et al., 2020). While biochar slightly increased soil water content in the rooting zone, the effect on the yield was most notable in dry years, enhancing biomass and grain production. In wetter years, biochar had little impact on yields. The biochar showed most effect under drought conditions. However, given the limited effect of biochar on yield, the study suggests selecting the right sorghum variety and planting time to be more effective for improving yields in the context of climate change.

A study from Nigeria confirmed that the AquaCrop model accurately predicted maize canopy cover, grain yield, and total biomass under various biochar, fertilizer, and irrigation treatments (Faloye et al., 2020). The model closely matched field data across two growing seasons, with minimal deviation. By adjusting key parameters- canopy decline coefficient (CDC), canopy growth coefficient (CGC), and water productivity (WP)- AquaCrop effectively captured the individual and combined benefits of biochar and fertilizer (Faloye et al., 2020). A similar approach is taken in this study, where a combination of biochar and fertilizer is evaluated against an untreated control.

1.3.6.4 Maize Stress Modeling in AquaCrop

In AquaCrop simulations of maize cultivation in semi-arid regions, the relationship between field capacity (FC), wilting point (WP), and soil moisture dynamics is essential for capturing crop responses to water stress. As soil water content declines from FC toward WP, maize undergoes a sequence of physiological stress responses, modeled by AquaCrop to reflect its sensitivity to drought. The first sign of stress is typically a reduction in canopy expansion, which helps the crop minimize water loss by limiting new leaf growth. If the stress continues, the model simulates stomatal closure, reducing transpiration and conserving water but also decreasing photosynthetic activity. Under prolonged stress- especially when soil water approaches the WP, early senescence is triggered, accelerating leaf death and reducing the green canopy cover essential for biomass accumulation. These stress responses are governed by crop-specific threshold values that define the depletion zones between FC and WP, allowing AquaCrop to simulate how maize adapts to short or long-lasting drought. This is particularly relevant in semi-arid environments, where rainfall is both limited and erratic, making efficient water use and timely stress responses critical for maintaining yield (Raes et al., 2009; Steduto et al., 2009).

1.3.6.5 Limitations to AquaCrop

When developing models to predict how something will behave, two types of uncertainty arise: data uncertainties – we do not know the exact values of some inputs - and model uncertainties, the model itself is simplified or lacks certain known process elements (Soize, 2005). Although AquaCrop is effective in modeling crop growth, it still has some inherent limitations. AquaCrop is designed to estimate crop yields on a single-field basis, assuming uniformity in crop growth, soil properties, and management practices across the field. It focuses solely on vertical water fluxes, including rainfall, irrigation, and capillary rise as inputs, and evaporation, transpiration, and deep percolation as outputs (FAO, 2024).

Another limitation to AquaCrop is that it does not simulate nutrient balances mechanistically. Instead, the model mimics fertility stress by adjusting crop development parameters like canopy cover and water productivity (Raes, 2023). This qualitative approach limits the model's ability to capture the full impact of nutrient-related processes such as mineralization or biochar-enhanced nutrient availability. This limitation is particularly relevant in studies focusing on soil amendments like biochar, where fertility effects may play a dominant role. As emphasized in model selection frameworks such as (Saloranta et al., 2003), the omission of such processes should be critically considered when evaluating model suitability for specific research questions.

While AquaCrop effectively models the effects of water availability on crop growth, it has limitations in accounting for any effects of certain soil amendments, such as biochar. For instance, a previously mentioned study by (Starr et al., 2020) investigated the impact of biochar on sorghum yield in South Sudan using AquaCrop. The model incorporated changes in soil hydraulic properties due to biochar application, based on meta-analysis data. However, the study also acknowledged that AquaCrop does not simulate the chemical effects of biochar, such as nutrient availability and microbial interactions, which can influence crop growth. This highlights a methodological uncertainty in the model's structure, as it may not fully capture the complex interactions between biochar and soil chemistry. Therefore, while AquaCrop can account for certain physical effects of biochar, it does not account for all the chemical and biological processes involved, leading to potential discrepancies between modeled and actual crop responses.

1.3.6.6 Uncertainties

It is also necessary to assess the uncertainties while conducting model simulations. A study from the Department of Hydrology in Copenhagen describes a framework for dealing with uncertainty due to model structure uncertanties (Refsgaard et al., 2006). While the uncertainties from input data and parameter values are commonly studied and well-handled, model structure uncertainty, the way the model conceptually represents reality, is often neglected and lacks a standardized method of assessment. Since all models are simplifications, mismatches between real-world systems and their modeled representations lead to inherent uncertainty. This issue becomes especially critical when models are used to predict beyond observed data, such as future scenarios (Refsgaard et al., 2006).

With respect to background data, the data used in this study were not collected by the author. Consequently, the analyses and simulations conducted rely on the accuracy and reliability of the provided data. Several miscalculations were identified during the process, which added complexity to the work. Thorough validation and quality control, measures have been implemented to ensure the usability of the dataset. Nonetheless, it is important to emphasize that the underlying data were not generated by the author, and the outcomes of this study are therefore dependent on the quality of the original dataset.

Chapter 2: Materials and Methods

This chapter provides a description of the study location and the implementation of the field experiment. It also presents a detailed account of how AquaCrop was used to calibrate the model using measured data from the experiment, as well as to perform simulations.

2.1 Software

2.1.1 AquaCrop

AquaCrop's standard program with graphical user interface and database version 7.1 is used in this thesis. This is the standard crop water productivity software model with Graphical User Interface (GUI) and database, developed by the Land and Water Division of FAO (FAO, 2025a).

2.1.2 Artificial Intelligence (AI)

Artificial Intelligence, represented by Sikt KI chat (Kunnskapsdepartementet, 2022), developed by the Norwegian Ministry of Education, and the model ChatGPT (OpenAI, 2025) have been used as a source of inspiration for developing ideas and perspectives, as well as for identifying relevant sources, whilst being critical to its potential bias and misinformation. It has specifically been contributing to precision and efficiency to the following:

1. Software troubleshooting: The AI-models have identified and corrected multiple errors in AquaCrop model input files, resulting in more efficient import of data.
2. Translation, language reading and proofreading: AI has provided suggestions for structural and linguistic changes to improve text quality.

The responses are critically assessed before relevant parts are used in the thesis.

2.1.3 R Studio

Statistical analyses and visualization of that were performed using R Studio, which is a statistical programming language and environment, offering efficient workflow for data processing, testing and plotting (R Core Team, 2024).

2.2 Site Description

The research was carried out in smallholder farmer fields in Embu, located in central Kenya (Figure 3). This location experiences two rainy seasons: March to July and October to December. Embu experiences an annual rainfall between 640 and 1495 mm, with temperatures varying from 15 to 25°C (Basalirwa et al., 2025). The location was an on-farm experiment and the site was chosen based on the farmers willingness to provide land for experimentation. Requirements for the experiment included fields with flat or gently sloping topography and fields managed similarly during the previous 2-3 cropping seasons, with maize monoculture and low amounts of organic and/or mineral fertilizers used. Table 1 summarizes key relevant information about the site.

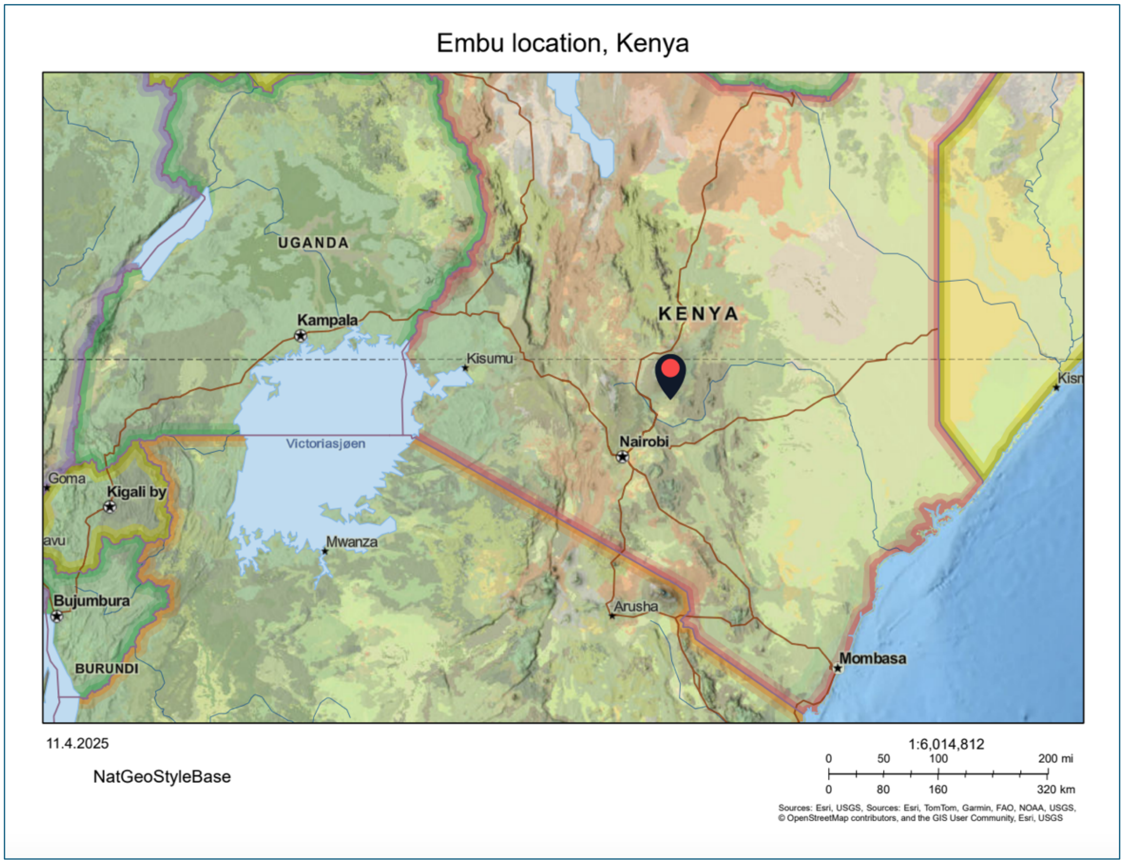

Figure 3. Experiment location, Embu in Kenya. Map is created with ArcGIS (ArcGIS, 2025).

Table 1. Overview of experiment location in Embu, Kenya (Basalirwa et al., 2025)

Specific location	**Latitude and longitude**	**Elevation in meters above sea level**	**Annual average rainfall(mm)**	**Soil type**	**Soil texture**	**Biochar feedstock**
Embu North (Hosea's farm)	-0.45° latitude, 37.45° longitude	1463	640-1495	Nitosols	Silty clay loam	Maize cobs

2.3 Selection of Treatments

Two treatments were selected from the experiment location. The selection was based on data availability and the agronomic performance of the treatments. The treatment with biochar 3 tons and fertilizer (BC3F) was chosen because it showed the highest biomass and yield in the field trial and had the most complete dataset available. This was then compared with the Control (C) treatment without any amendments. Average values based on data from three blocks for each treatment was used for further model calibration.

Ideally, the treatment consisting of 6 tons of biochar without fertilizer would have been selected, as it would allow for a clearer assessment of the isolated effect of biochar application. However, complete datasets were not available for this treatment, and the analysis was therefore limited to the treatments with available data: BC3F and C.

2.4 Experimental Set up and Land Preparation

The experimental field work was conducted by other members of the BICEPS-team, and is described below, according to (Basalirwa et al., 2025).

The experiment was conducted on farmer fields in Embu, with treatment plots measuring 4 × 4 m (16 m^2). The site included the following treatments: Control (C), Fertilizer (F), Manure (M), 3 ton/ha biochar (BC3), 6 ton/ha biochar (BC6), Fertilizer + 3 ton/ha biochar (BC3F), Manure + 3 ton/ha biochar (BC3M), and Manure + 6 ton/ha biochar (BC6M). The treatments were arranged in a randomized complete block design (RCBD) with three replicates, and 0.5 m wide buffer zones separated the blocks (Figure 4). Control plots received no fertilizer, manure, or biochar (Basalirwa et al., 2025). Maize cob biochar was applied in the field, with the choice of biochar type based on local feedstock availability. Biochar was produced using flame-curtain "Kon Tiki" kilns in conical open soil pits (Cornelissen et al., 2016) and crushed to particle sizes ≤10 mm before application.

Land preparation included careful removal of weeds from each plot using a small hoe, taking care not to disturb the biochar previously applied in the furrows. The soil was then gently loosened to preserve the positioning of the biochar within the treated areas. Each plot was organized with five furrows, whose positions were maintained using root stumps, ropes, and pegs as guides. To ensure uniformity, the furrows were reopened to a depth of 15 cm with a hoe, and the displaced soil was temporarily placed nearby. The ropes were kept in place throughout the process to accurately relocate the furrows. Once the furrows were reopened, each field was marked with ropes in a 4 by 4 meter layout to delineate the plots clearly, allowing for precise application of manure and fertilizer. This entire procedure was consistently repeated across all three blocks to facilitate efficient management and ensure accurate implementation of the treatments.

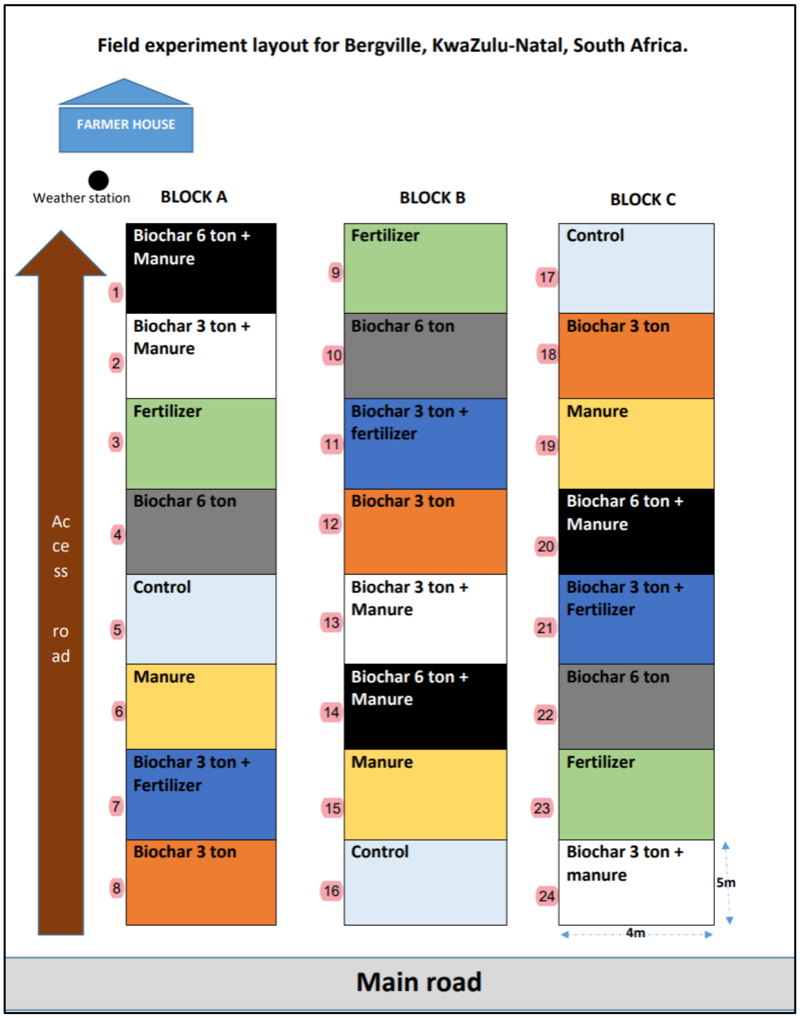

Figure 4. Experimental layout for maize plants in Okhalamba field experiment in the Republic of South Africa. Almost identical setup was conducted in Embu, Kenya.

2.5 General Soil Data

The soil from the field experiment location was categorized as Nitosols by other members of the BICEPS-team and is also confirmed by other sources (Ouma et al., 2002). The Nitosols are considered old and weathered, but of great importance to the local agriculture (Hirose, 1987). These deep, well-drained, reddish to dark yellowish-brown clayey soils found throughout the tropics and subtropics, are known for their distinctive shiny, blocky or nutty structure. They have high aggregate stability, good porosity, and moisture retention. Formed from basic rocks or volcanic ash-enriched sediments, they are friable and often magnetic. These soils often support high population densities under subsistence farming and are widely used for commercial crops (Creutzberg & Sombroek, 1987).

General soil fertility in this region varies from high fertility in the forest zones of Mount Kenya and nearby highlands, but decreases to moderate and low levels in the lower midland zones. Soil depth also varies, with deep soils in the upper midlands and shallow soils in the lower midlands (Ndirangu, 2017). The depth of the soil in the field trial was measured to 1,4 meters. Before the establishment of the experiment and before any applications of inputs, baseline soil sampling was conducted in each of the 24 plots, at five different locations. The upper 2 cm of the soil was removed and a soil sample taken down to around 15 cm depth using a small garden spade. The five samples were placed in a bag and mixed to get one composite sample from each of the plots (n = 24 from each site). A sub-sample from the five mixed soil samples was air-dried, ground, sieved through 2 mm and transferred to a plastic bag before chemical analysis. However, the chemical properties from the different plots were not yet analyzed by the time of this thesis submission, but it is likely to suspect that the Control showed rather low fertility and BC3F showed significantly higher values.

The soil texture triangle (Figure 5) was used to determine the soil types with the use of averages from the three blocks in the field experiment. The soil was categorized as silty clay loam.

Figure 5. United States Department of Agriculture Soil Texture Triangle (Groenendyk et al., 2015).

The physical soil analyses (soil water retention) were conducted at the University of Nairobi, at the Soil and Water Engineering Lab. The chemical properties were analyzed at the Norwegian University of Life Science (NMBU) in Ås, Norway. However, as mentioned previously, the results from the chemical analysis was net yet finished by the time of thesis submission.

2.6 Climate Data

Daily weather data for Embu, Kenya, was retrieved from the NASA POWER (Prediction Of Worldwide Energy Resources) database (Table 2). The data was accessed via the POWER Data Access Viewer by entering the coordinates for Embu and selecting relevant climate variables such as precipitation and temperature for the study period (NASA POWER Project, 2024).

Due to uncertainties associated with the rainfall data from NASA Power, a simple test was conducted in AquaCrop. It was unlikely that it rained every day, as suggested by the NASA data, and based on insights from local knowledge, all days with less than 1 mm of recorded rainfall were set to to 0 mm in the climate file. This was then run in the model to see if there was any significant change to the outcome. The results from this test is presented in Table 3.

Table 2. Climate parameters for input data in AquaCrop, retrieved from NASA Power.

Date	Tmin	Tmax	Solar rad	Wind at 10 m	RHmean at 2 m	Rainfall
DDMMYYYY	*C	*C	MJ/m^2	m/s	%	mm
01.04.2024	17,76	25,26	20,4	2,81	83,99	16,81
02.04.2024	17,49	26,84	19,38	2,52	80,64	6,29
03.04.2024	17,21	26,78	20,19	2,55	80,2	5,93
04.04.2024	16,77	23,71	16,77	2,22	87,27	15,67
05.04.2024	17,03	25,57	20,55	2,51	83,76	11,5
…	…	…	…	…	…	…
28.09.2024	15,05	28,31	24,05	1,94	74,27	4,48
29.09.2024	15,1	26,84	25,94	1,89	72,33	1,19
30.09.2024	14,91	28,03	23,42	2,14	70,94	0,82

From April 1st to around mid-May, and especially from April 14th (the sowing date) onward, there are many days with high rainfall amounts (>20 mm per day), high relative humidity (>85%) and moderate temperatures(Figure 6; Figure 7; Figure 8). This creates a risk of waterlogging, oxygen deficiency in the root zone, inhibited germination and eventual early growth. However, the emergence is at day 7, so the stress is not affecting the maize growth severely. There is, on the other hand, a dry period around the time of flowering which could potentially stress the plant during a critical phase.

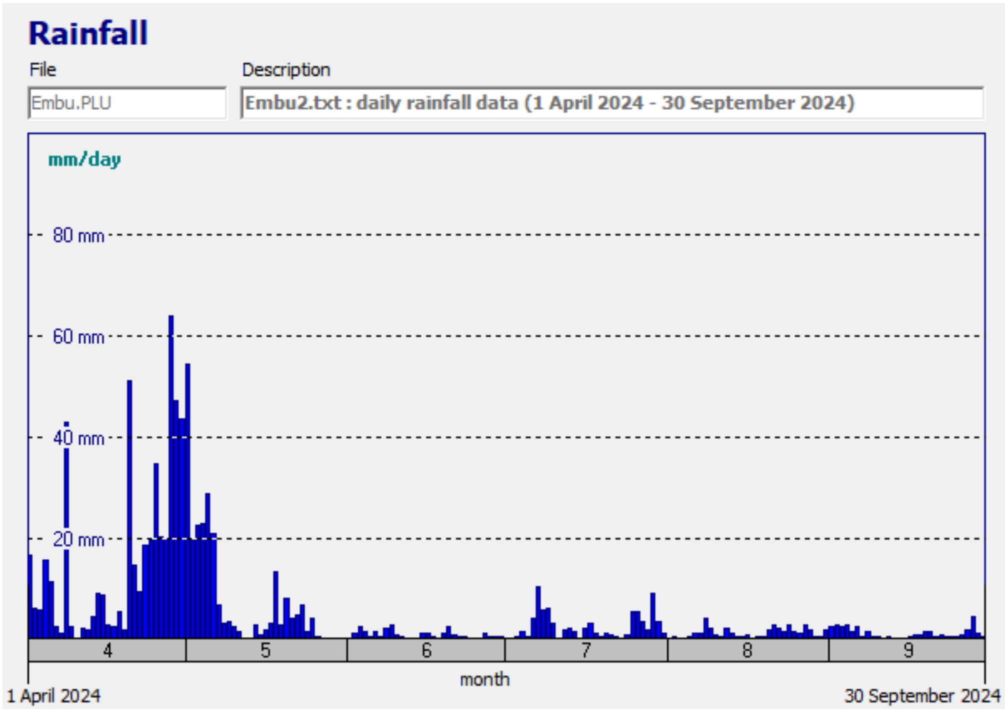

Figure 6. Rainfall in Embu from 1st of April to 30th of September 2024. Data retrieved from NASA Power (NASA POWER Project, 2024) and visualised in Aquacrop.

The test that was conducted by removing all daily rainfall events below 1 mm decreased the total seasonal rainfall by 28.6 mm (from 800.4 mm to 771.8 mm). Interestingly, it resulted in a slightly higher biomass (+0,07 ton/ha). The model also showed a reduction in evaporation (-28.7 mm) and a minor increase in transpiration (+0.3 mm). These results suggest that excluding very small rain events may reduce water loss through soil evaporation, thereby slightly enhancing water use efficiency in the model. However, this adjustment had only a minor effect on yield and water balance components and was therefore considered to not have substantial impact on the overall simulation outcome.

Table 3. Results from simple test in AquaCrop, comparing the outputs from simulations using climate files with and without days with rainfall <1 mm.

Component	NASA Data	Without <1mm=0
Rainfall	800.4 mm	771.8mm
Evaporation	339.3 mm	310.6
Transpiration	87.7 mm	88.0 mm
Runoff	230.7 mm	231.0 mm
Infiltration	569.7 mm	540.8 mm
Biomass	7.48 ton/ha	7.55 ton/ha
Yield	3.26 ton/ha	3.27 ton/ha

Figure 7 shows the daily reference evapotranspiration (ETo) in Embu from April 1 to September 30, 2024. Throughout the period, ETo generally ranges between 2 and 5 mm/day early in the season but gradually increases toward late summer and early autumn. Toward the end of the period, particularly in August and September, ETo rises noticeably, often exceeding 6 mm/day. This reflects drier weather and increased evaporation, meaning that crops during this time experience higher water demand and an increased risk of drought stress in the dry season, especially in rainfed systems.

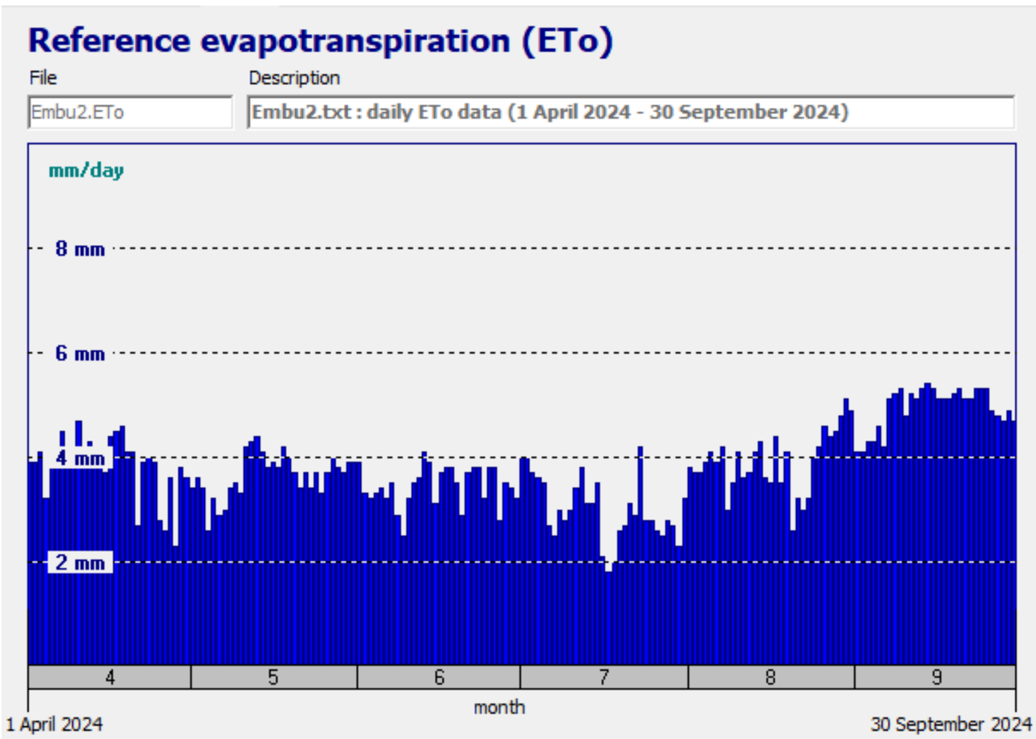

Figure 7. Reference evapotranspiration through from 1st of April to 30th of September.

Daily maximum and minimum air temperatures for the period 1 April to 30 September 2024 that were used as input in the model is shown in Figure 8. Maximum temperatures (Tmax) generally ranged between 24 °C and 30 °C, while minimum temperatures (Tmin) stayed between 10 °C and 17 °C. A slight drop in both Tmax and Tmin was observed around June and July, reflecting seasonal variation.

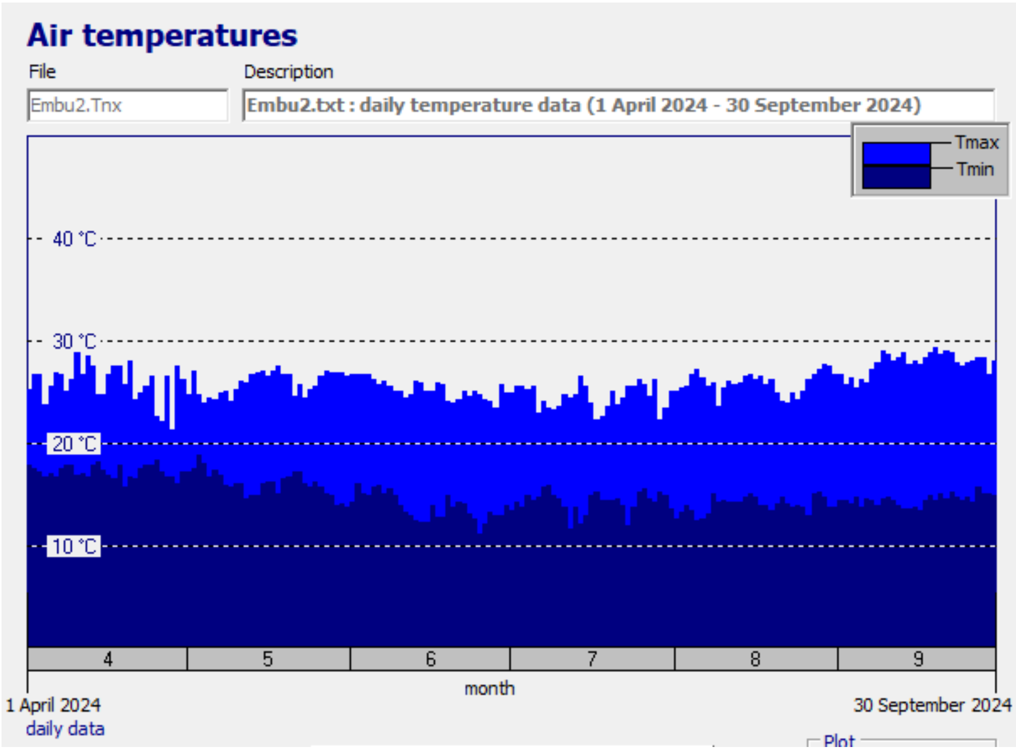

Figure 8. Daily air temperatures in Embu from 1st of April to 30th of September 2024.

2.7 Root Development

Root development was measured using averages from the treatments. BC3F reached a rooting depth of 0,56 meters after 75 days and the control reached 0,33 meters after 80 days. This is very shallow roots, especially for the Control, and is considered the minimum rooting depth for maize (Raes et al., 2023b). To put it in context, the maize roots can reach up to 2,5 meters according to the AquaCrop Reference Manual.

2.8 Crop Data

The relevant crop data includes canopy development, plant density and rooting depth and is listed in Table 4.

Table 4. Crop parameters for both treatments measured from the BICEPS project.

Parameter	BC3F	Control
Sowing/harvesting date	14/04 - 24/09/2024	14/04 - 24/09/2024
Emergence days after sowing	6 days	7 days
Flowering days after sowing	67 days	72 days
Maximum CC days after sowing	140 days	140 days
Canopy senesence days after sowing	147 days	148 days
Maturity days after sowing	157 days	158 days
Maximum CC %	95 %	66 %
Plant density	60 740 plants/ha	40 987 plants/ha
Maximum rooting depth	0.56 cm	0.33 cm

Measured canopy cover for the two treatments is presented in Figure 9. Both treatments reached their maximum canopy cover approximately in week 20 after sowing. BC3F reaches a maximum CC of 95% and Control 66%. The slight variations observed before and after this point are likely due to minor inaccuracies in data collection.

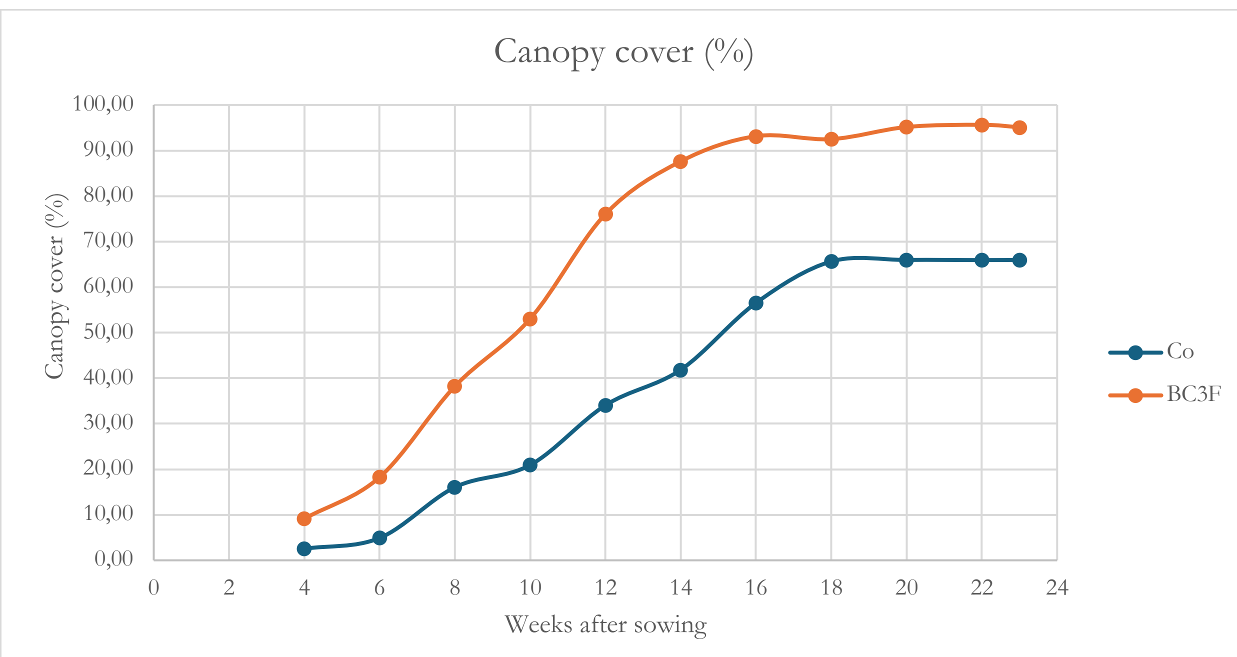

Figure 9. Canopy cover (%) weeks after sowing for both treatments.

2.9 Soil Water Retention

The BC3F treatment shows slightly lower water retention than the Control across parts of the curve in Figure 10, though the difference is minimal around field capacity. At wilting point, BC3F appears to retain slightly more water than the Control. Overall, the differences are small, and due to noticed inconsistencies in the delivered data, a statistical analysis was conducted to investigate the deviations.

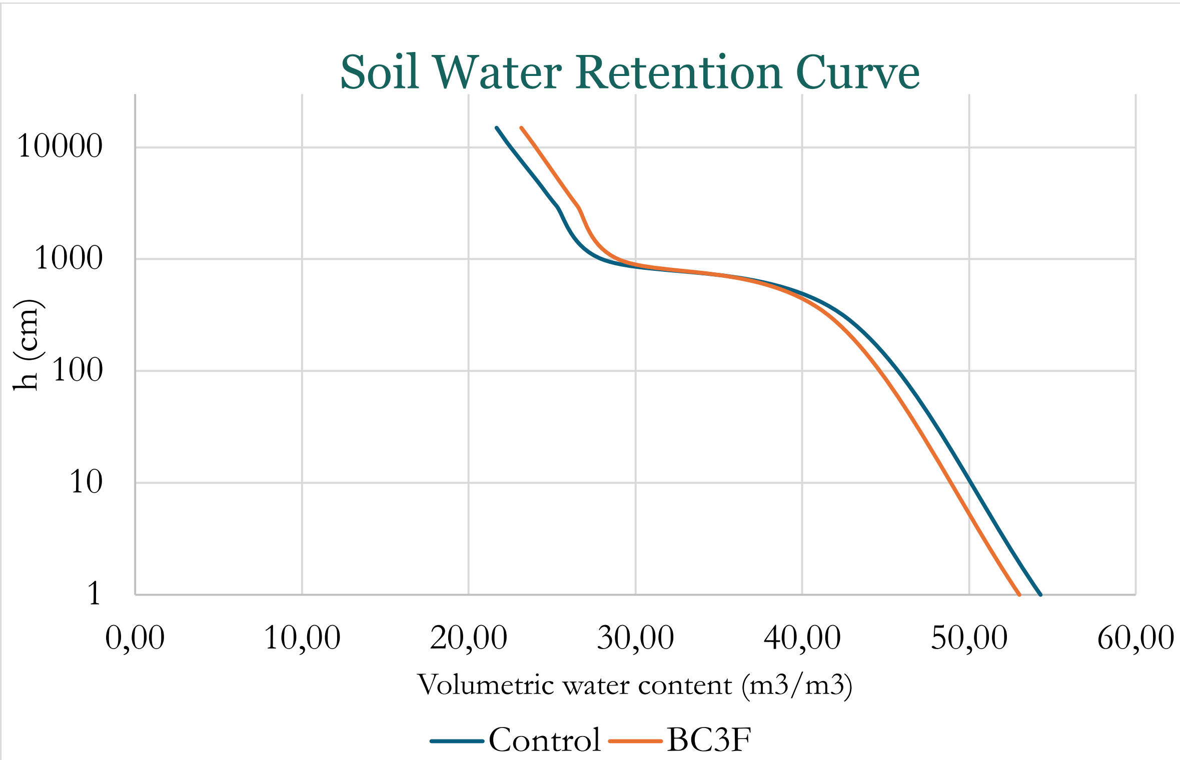

Figure 10. Soil water retention curve for BC3F treatment and the Control.

To examine potential differences in initial soil conditions between treatments, statistical comparisons were conducted using two approaches. First, an analysis of variance (ANOVA) was performed across all eight treatments, followed by Tukey's post-hoc test for pairwise comparisons. This analysis revealed no significant differences ($p > 0.05$) for any of the measured soil hydraulic properties, including saturation (SAT), field capacity (FC), permanent wilting point (PWP), available water content (AWC), bulk density (BD), and saturated hydraulic conductivity (Ksat) (see Appendix X).

In a second analysis focusing only on the Control and BC3F treatments, Welch's two-sample t-tests were used to account for potential differences in variance between groups. Again, no statistically significant differences were found ($p > 0.05$), further supporting the assumption that the two treatments had comparable baseline soil conditions. All statistical analyses were conducted in R version 4.4.2 (R Core Team, 2024).

2.10 Data Preparation and Calibration for AquaCrop

Since the data was provided by other members of the BICEPS team, the next step in the process involved organizing and converting the data into text files compatible with AquaCrop. Data import procedures followed the guidelines outlined in the AquaCrop Training Handbook (Raes & Van Gaelen, 2016) and the instructional videos developed by the FAO (FAO, 2021).

2.10.1 Model Set Up

Figure 11 shows the main menu in Aquacrop with relevant files marked. The same climate file was used for both calibrations. Climate parameters included temperature (max and min), solar radiation, windspeed, relative humidity and rainfall (Table 2). The weather data was retrieved from NASA Power using longitude and latitude, as the local weather station stopped collecting data at some point, due to unidentified reasons. AquaCrop required the altitude of the location(1463 meters above sea level) and latitude in decimal (0.4527607 degrees south). The file imported ranged from 1 April 2024 until 30 September 2024, a little before and after sowing and harvesting. This made it possible to change sowing dates during simulations.

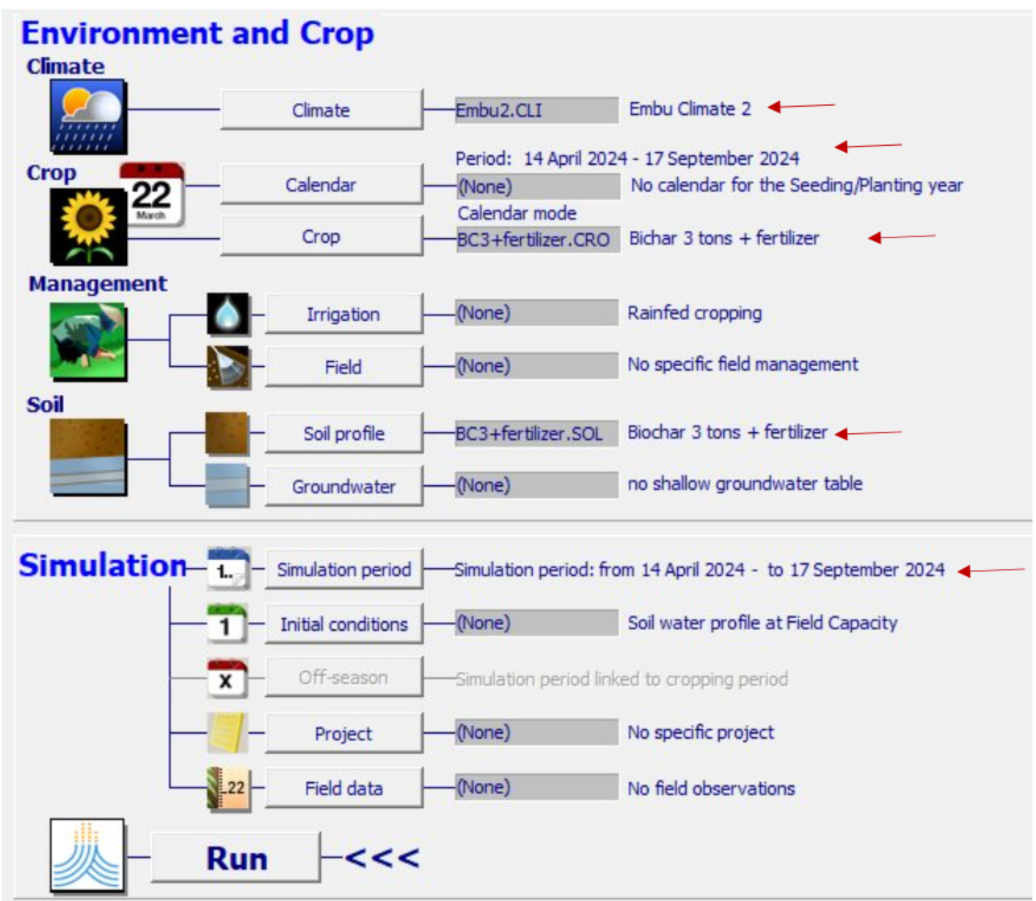

Figure 11. Input files that were imported to AquaCrop before running the model. Red pointers mark the selected input files.

To adjust crop transpiration and biomass water productivity, AquaCrop also requires input on the mean annual atmospheric CO_2 concentration, which is found in the input file from AquaCrop called 'MaunaLoa.CO2'. The file contains mean annual atmospheric CO_2 concentrations measured at the Mauna Loa Observatory from 1958 onward. For earlier years, values are reconstructed from firn and ice core data, while future concentrations are estimated using a projected annual increase of 2.0 ppm, which is considered a reasonable assumption for the coming decade (Raes & Van Gaelen, 2016). In this simulation for 2024, the atmospheric CO2 concentration was set to 422.57 ppm, following the default 'MaunaLoa.CO2' file in AquaCrop .

Soil and crop input files were developed for the Control (C) and biochar 3 tons with fertilizer (BC3F) treatments based primarily on field-measured data. Due to gaps in the available dataset, several parameters were supplemented using the default values in Aquacrop and other relevant literature. For example, the flowering period was defined based on literature values (Paleontological Research Institution, n.d; Purdue University Department of Agronomy, 2002).

These input files formed the basis for the calibration of the AquaCrop model, with the purpose of enabling its use in future scenario analyses, such as testing the effect of changing sowing dates. The calibration aimed to align simulated outputs with observed field measurements as closely as possible.

2.10.2 BC3F-calibration

To achieve this match of biomass, adjustments were made to selected model parameters known to significantly influence biomass output. For the BC3F treatment, the maximum rooting depth was reduced slightly from the measured value of 0.56 m to 0.52 m. In addition, the crop water productivity (WP*), normalized for climate and CO_2 concentration, was set to 28 g/m^2. The crop's sensitivity to soil water stress was increased by adjusting the thresholds for stomatal closure, canopy expansion, and early senescence from moderate to sensitive levels for the BC3F treatment. The specific parameters that were used and calibrated are listed in Table 5.

These three parameters - rooting depth, water productivity, and stress response thresholds - were prioritized during calibration due to their high sensitivity. Rooting depth is dynamic and influenced by soil conditions and water availability, affecting the plant's ability to access water and nutrients . Water productivity directly links transpiration to biomass production, making it a critical parameter for yield estimation. Stress thresholds define how the crop responds to water deficits and regulate processes like stomatal behavior and canopy senescence. Calibrating these parameters ensured that the simulated crop development reflected observed field performance under local conditions to the degree possible (Raes et al., 2023a).

The crop's sensitivity to soil water stress was increased by adjusting the thresholds for stomatal closure, canopy expansion, and early senescence from moderate to sensitive levels for the treatment.

During the calibration process, several adjustments were necessary to achieve the targeted biomass. Both water productivity (WP) and rooting depth were tested across different ranges and proved to be highly sensitive parameters. In this specific calibration, the shallow rooting depth and water limitation in the topsoil made rooting depth particularly influential. Although WP is considered a conservative parameter, the selected value of 28 g/m^2 remains within the default range for C4 crops in AquaCrop.

2.10.3 Control Calibration

The calibration of the Control treatment proved to be demanding. At first, the model produced no yield due to very low simulated biomass. As described in the FAO AquaCrop documentation, yield formation depends on sufficient biomass accumulation. Without enough biomass, the Harvest Index(HI) does not begin to build up (Raes et al., 2023a). The calibration used the parameter values listed in Table 5, but to reach the measured biomass of 2.37 ton/ha, several adjustments were needed. Water Productivity (WP) had to be lowered to 20 g/m^2. This value lies within the typical range for C3 crops, not C4, which maize is, and this represents a clear weakness in the calibration. Although the adhustment helped approximate the observed biomass, it undermines the reliability of the simulation, as the WP no longer reflects the physiological characteristics of the crop type being modeled.

To reflect canopy development in the field, the time of maximum canopy was set to 126 days(week 18). The HI was set to 42%, the same as for the BC3F, as described by members of the BICEPS team. Soil fertility stress was reduced to about 50% in the crop file, and defined as “moderate” in the management file, to reflect nutrient limitations. The model was not able to run a simulation if the fertility level was set any lower than this.

The maximum rooting depth for the Control was increased slightly, from the measured 0.33 meters to 0.35 meters. Since this parameter is known to be highly sensitive, and minor deviations in field measurements are not uncommon, the change was considered acceptable. The crops response to stresses was also set to “sensitive”, consistent with the BC3F calibration.

Table 5. Parameters used in AquaCrop for calibration of the model for the two selected treatments.

Parameter	BC3F	Control	Comment
Soil Parameters			
Soil texture	Silty clay loam	Silty clay loam	Measured from project
Wilting point (PWP)	22,66 m^3/m^3	22,66 m^3/m^3	Measured from project
Field capacity (FC)	40,77 m^3/m^3	40,77 m^3/m^3	Measured from project
Saturation	51,76 m^3/m^3	51,76 m^3/m^3	Measured from project
Saturated hydraulic conductivity (Ksat)	1862,4 mm/day	1862,4 mm/day	Measured from project
AWC%	18,11	18,11	Measured from project
Soil depth	1,4m	1,4m	Measured from project
Crop Parameters			
Initial canopy cover	0.30%	0.20%	Estimated by Aquacrop
Plant density	60740 plants/ha	40987 plants/ha	Measured from project
Type of planting method	Direct	Direct	
Crop type and variety	C4	C4	Maize
Sowing/harvesting date	14/04 - 24/09/2024	14/04 - 24/09/2024	
Emergence days after sowing	6 days	7 days	Measured from project
Flowering days after sowing	67 days	72 days	Measured from project
Duration of flowering	15 days	15 days	Based on litterature
Maximum CC days after sowing	140 days	126 days	Measured from project/Calibrated
Canopy senesence days after sowing	147 days	148 days	Measured from project
Maturity days after sowing	157 days	158 days	Measured from project
Maximum CC %	95 %	66 %	Measured from project
Water productivity (WP) parameter	28 $g/m^2/MJ$	20 $g/m^2/MJ$	Calibrated
Maximum rooting depth	0.52 cm	0.35 cm	Calibrated
Max rooting depth days after sowing	75 days	80 days	Measured from project
Harvest index (HI)	42	42	Described by members of BICEPS
Soil fertility stress calibration	Not considered	Moderate stress	
Field Management Parameters			
Rainfed or irrigated	Rainfed	Rainfed	
Soil fertility	Not considered	50 %	
Sowing	Direct	Direct	
Soil water stresses			
Canopy expansion	Sensitive	Sensitive	Calibrated
Stomatal closure	Sensitive	Sensitive	Calibrated
Early canopy senescence	Sensitive	Sensitive	Calibrated
Aeration	Sensitive	Sensitive	Calibrated

2.11 Model Predictions for Changed Sowing Date

To explore the predictive potential of the model and assess possible management adjustments available to farmers, the effect of changed sowing date was examined. After completing model calibration, alternative sowing dates were tested to evaluate potential advantages or disadvantages in terms of yield outcomes. To assess the potential impact of sowing date on crop productivity, predictions were conducted by running AquaCrop simulations using six alternative sowing dates. These included three earlier (3, 7, 10 and 13 days before the actual sowing date) and three later (3, 7, 10 and 13 days after). This was done in the calendar file in AquaCrop by changing the date from 14th of April to the respective dates. The BC3F treatment was used for all simulations, and output variables included total biomass, yield, and stress indices for canopy expansion, stomatal closure, and early senescence.

Chapter 3: Results

3.1 Simulation Results

3.1.1 BC3F-Treatment Simulation

The AquaCrop simulation for the BC3F treatment illustrates crop development, water balance, and stress dynamics throughout the growing season, ending on 17th of September 2024. The total simulated aboveground biomass reached 7.480 ton/ha, and the corresponding grain yield was 3.257 ton/ha, indicating a moderate to productive growing season. This corresponds closely with the measured dry biomass of 7.23 ton/ha. The simulation also provides an estimate of the potential biomass under ideal conditions - i.e., in the absence of water stress, with unlimited soil fertility, no salinity stress, and no weed infestation - amounting to 24.57 ton/ha. While such conditions are highly unlikely to occur in the field, this estimate serves as an indication of the biomass that could be achieved under reduced stress levels.

However, several water-related stress factors were identified. The model reports average and daily stress levels experienced by the crop. The crop experienced moderate average stress levels throughout the growing cycle: canopy expansion stress averaged 49%, stomatal closure 16%, and early senescence 48%. Soil fertility stress averaged 55%, indicating suboptimal but not critical nutrient availability. These moderate stress levels allowed for continued development, though some limitations in growth and water use efficiency were likely.

In the early stages, overall stress levels are low, although there is some moderate stress related to stomatal closure during the first 20 days after planting, after stomata had formed. At flowering, the plants experienced severe canopy expansion stress (up to 100% on certain days). At the same time there was depleted soil moisture in the upper 20 cm (Figure 12). Although water was present in the soil profile, the plant still experienced stress, possibly due to limitations in root water uptake efficiency or uneven distribution of moisture.

While the overall depletion decreased slightly around flowering, seen in Figure 13, this did not reflect improved water conditions in the upper soil layers, likely where most of the root activity was concentrated. The simulated soil water profile (Figure 12) suggests that much of the remaining moisture was stored deeper in the profile, beyond the reach of the shallower roots. This limited accessibility may have contributed to continued canopy expansion stress. However, another contributing factor could be the overall water balance: despite earlier rainfall, the amount of water available during this stage may have been insufficient to meet the combined atmospheric demand for transpiration and evaporation. In this case, the water stress may not only be explained by poor vertical water distribution, but also by a general rainfall deficit relative to evapotranspiration demand.

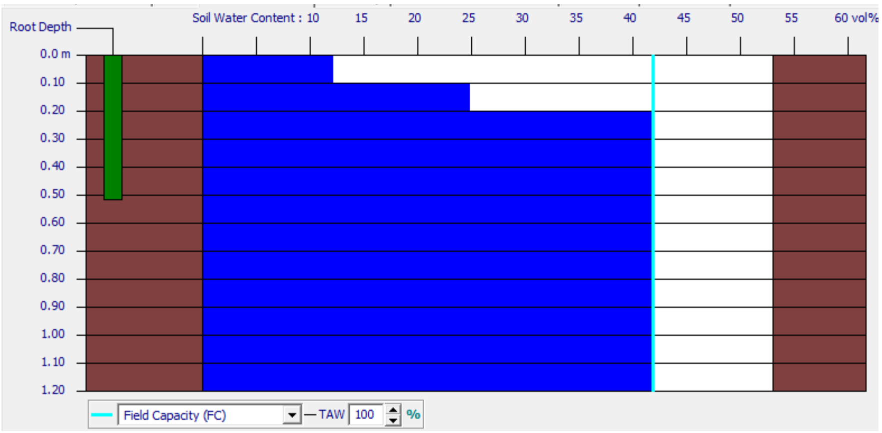

Figure 12. Simulated soil water profile one day during flowering for BC3F.

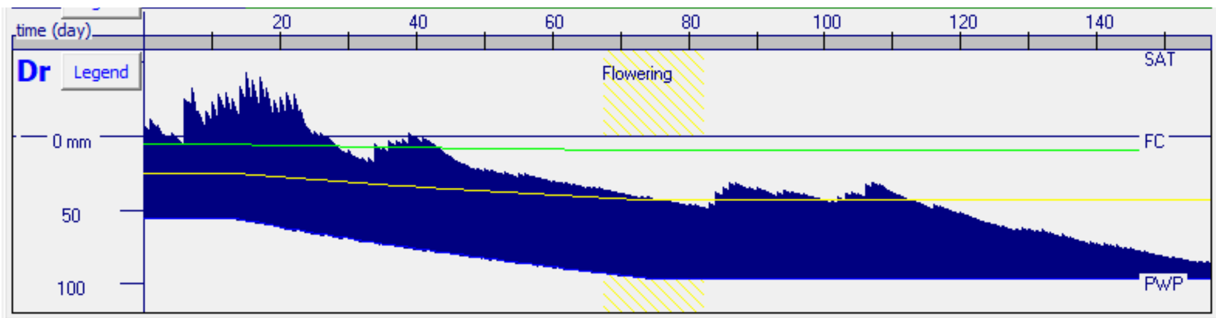

Figure 13. Depletion in the root zone for BC3F simulation, flowering is highlighted in yellow.

During the cropping period, total reference evapotranspiration (ETo) was 575.4 mm. Of this, the model estimated a potential crop transpiration (Trx) of 121.4 mm, but actual crop transpiration (Tr) was only 87.7 mm, indicating that the crop experienced significant water limitations. Most water loss occurred through evaporation from the soil surface (506.9 mm), especially during the early growth stages when canopy cover was still low. Although infiltration was high (569.7 mm), limited rooting depth and rainfall intensity meant that a substantial portion of the infiltrated water (228.7 mm) drained below the root zone and was unavailable to the crop. As a result, the crop experienced water stress, leading to moderate yield and relatively low water productivity.

Table 6. Soil water balance output parameters from the simulations.

Parameter	BC3F (mm)	Control (mm)	Comment
Ex	506.9	577.9	Evaporation from soil surface all season
E	339.3	355.1	Evaporation in growing cycle
Trx	121.4	50.0	Potential transpiration
Tr	87.7	41.8	Actual transpiration
Infiltration	569.7	570.8	Almost all rain was infiltrated
Runoff	230.7	230.7	A lot of rain lost, likely due to heavy rainfalls
Drained	228.7	228.6	Water not available to plants

The Canopy Cover (CC) graph in Figure 14 displays both actual (green bars) and potential (grey shaded area) canopy development for the BC3F treatment. The grey area represents the potential maximum CC which was inserted in the input file, based on the measured data, which was 95%. It never reaches its full potential, most likely due to accumulated water stress throughout the season. This reduction in green cover limited biomass accumulation and yield potential. The simulated canopy cover is highly different from the measured. This is likely due to the stress factors that were necessary to be added to get to the measured biomass.

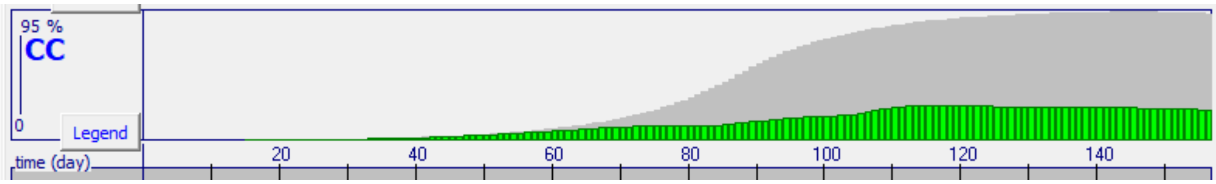

Figure 14. Canopy development in BC3F simulation. Green bars display actual development, whilst grey bars show potential canopy cover.

In conclusion, the BC3F treatment yielded moderate productivity under conditions of substantial water stress. Despite the presence of biochar and fertilizer, water limitations - especially during the flowering period - constrained the crop's physiological processes and yield potential. These findings highlight the importance of water availability in determining the success of soil amendment strategies, even when nutrients are sufficiently supplied, or when the water is limiting.

3.1.2 Control Simulation

The Control simulation reached a biomass production of 2.59 ton/ha and yield of 1.15 ton/ha. This simulation also corresponds with the measured biomass (2.37 ton/ha). The potential biomass suggested by the simulation is 14.4 ton/ha. The simulation also suggest that high stress levels has hindered proper yield development, with an average stomatal closure of 17%, canopy expansion of 55% and 22% soil fertility stress. Similarly to the BC3F simulation, the Control simulation also struggled with reproducing observed canopy cover, and underestimated it at a slightly higher rate than the BC3F.

Figure 15 illustrates a clear mismatch between rainfall distribution and crop water requirements. While substantial rainfall occurs early in the season(displayed closer in Figure 6 - rainfall), the first 25 days, precipitation declines afterwards, leading to prolonged dry conditions. The depletion in the root zone (Dr-graph in Figure 15) shows that soil moisture drops steadily and remains below field capacity (FC) for most of the growing period. During the flowering stage (highlighted in yellow) the soil moisture remained well below field capacity and showed increasing depletion, indicating developing water stress, although not yet at the permanent wilting point (PWP). This stress likely made it harder for the plant to form a proper crop, which explains the low biomass and yield produced. After the flowering, around day 80 there is continued dry conditions, with occasional light rainfall events that temporarily improve the soil water status. The soil remains generally dry towards the end of the season.

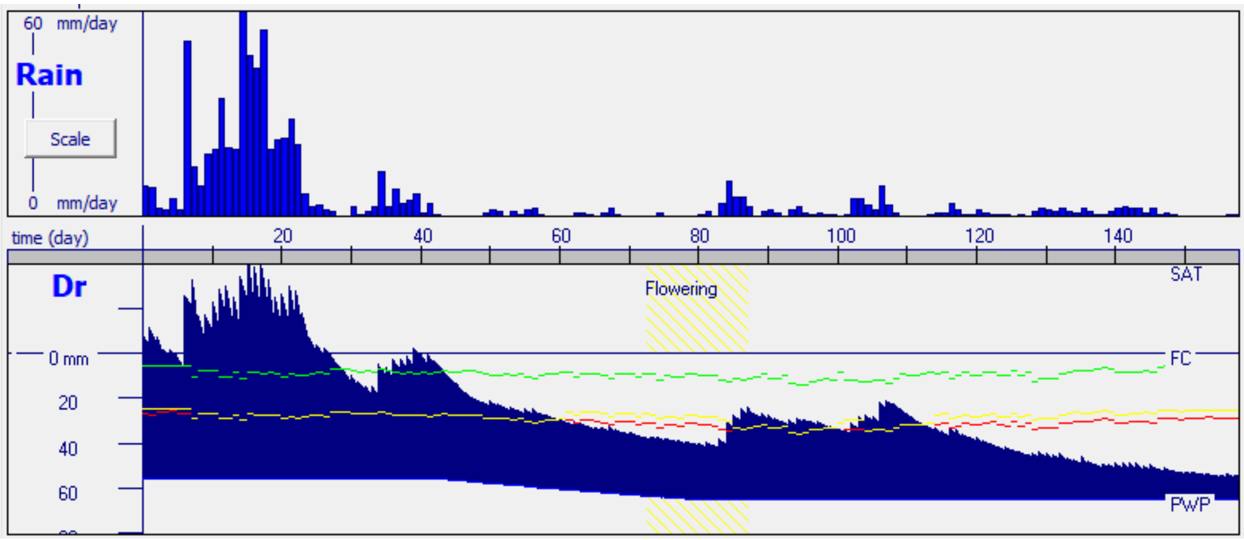

Figure 15. Root zone depletion for Control treatment and rainfall during the growing season.

The soil water balance results in Table 6 indicate inefficient water use during the growing season. Despite receiving 801.5 mm of rainfall, no irrigation was applied, and a significant portion of the water was lost through surface runoff (230.7 mm) and deep drainage (228.6 mm). Only 41.8 mm was used for actual transpiration, while a large share (577.9 mm) was lost as soil evaporation, likely due to limited canopy development. The potential transpiration (Trx) was only slightly higher at 50 mm, suggesting that stress limited overall crop growth rather than directly restricting water uptake. These results are consistent with the low canopy cover and biomass production observed in the simulation.

While the calibration produced biomass values close to the field measurements, the use of WP value characteristic of C3 crops could indicate a limitation in the models ability to realistically simulate nutrient-stressed C4 crops like maize. This compromises the reliability of the simulation and should be taken into account when interpreting the results.

3.1.3 Prediction for Changed Sowing Dates

The results from the change of sowing date show a clear trend: simulated biomass production decreased progressively with later sowing dates. Biomass ranged from 8,210 ton/ha when sown 13 days earlier to 6,698 ton/ha when sown 13 days later (Figure 16; Appendix 2). Yield followed a similar pattern, declining from 3.574 to 2,916 ton/ha (Figure 17; Appendix 2). Stress indices also reflected this trend: average stomatal closure and early senescence increased with each delay in sowing, while canopy expansion stress remained relatively stable.

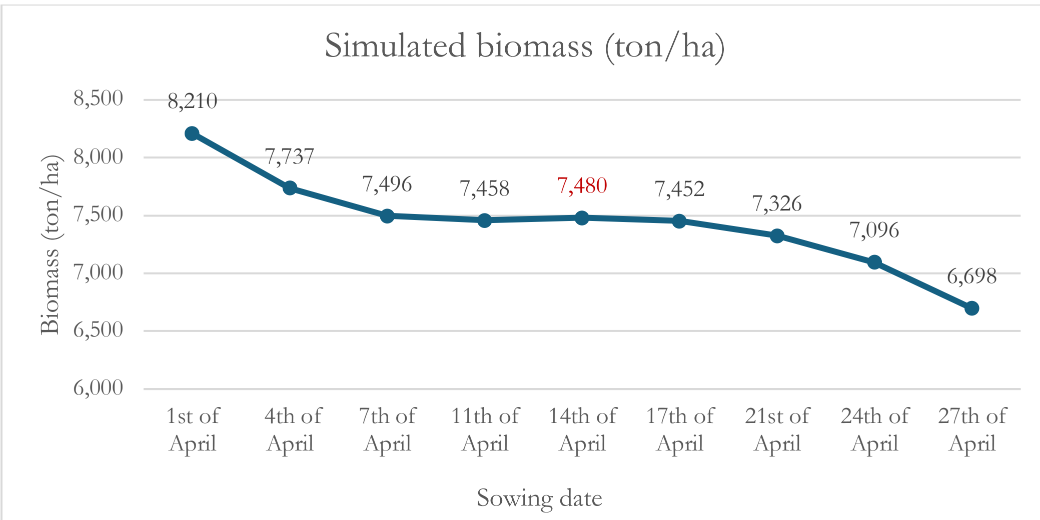

Figure 16.Simulated biomass for changed sowing dates for BC3F treatment ranging from 13 days before sowing date(14th of April) to 13 days later

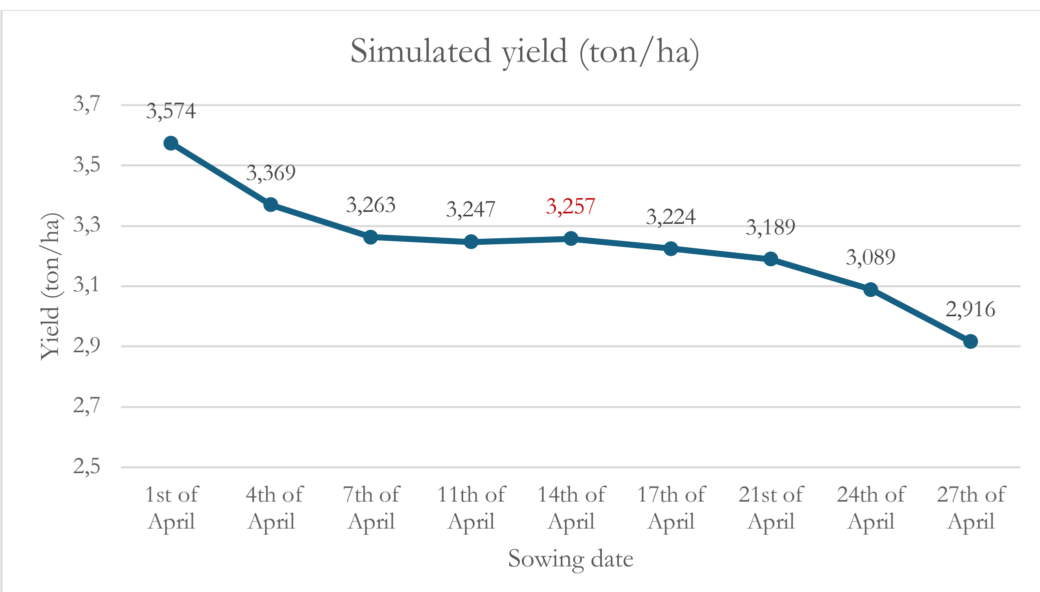

Figure 17. Simulated yield for changed sowing dates for BC3F treatment ranging from 13 days before sowing date(14th of April) to 13 days later.

Chapter 4: Discussion

The results from this study are interpreted in this chapter in light of the research objectives, focusing on model performance, treatment effects, sowing date and broader implications. Each subsection addresses one or more of the research questions posed in Chapter 1.2. The discussion integrates field observations with AquaCrop simulations and relevant literature on biochar, crop modeling, and soil-water-plant interactions in sub-Saharan Africa to answer the key questions.

4.1 AquaCrop Model Performance vs. Field Observations

4.1.1 Calibration Success and Yield Matching

A key objective was to determine whether the FAO AquaCrop model, after calibration, could reproduce the observed field results. The calibration revealed both its strengths and limitations in simulating maize growth under varying fertility conditions. After extensive fine-tuning of various parameters in the model, a simulated biomass value was eventually achieved that closely matched the observed field data. The calibrated simulation for the BC3F treatment produced 7.48 t/ha above-ground biomass and 3.26 t/ha grain yield, closely aligning with the observed 7.27 t/ha, respectively. The Control simulation likewise achieved biomass in the order of 2.6 ton/ha and yield 1.15 ton/ha vs. 2.37 ton/ha biomass observed. These matches indicate that, in terms of final outputs, AquaCrop could be calibrated to reproduce the field data with reasonable accuracy. This alignment was primarily accomplished by increasing the sensitivity of multiple stress parameters (Table 5), as well as calibrating the rooting depth and adjusting the water productivity (WP).

4.1.2 Canopy Development and Model Limitations

Despite matching final biomass, the model struggled to reproduce the observed canopy development over time (Figure 9: Canopy Development; Figure 14: CC in AquaCrop). The simulation show significantly lower values throughout the growing season. AquaCrop significantly under-predicted canopy cover in the treatments, especially for the Control and the simulated canopy stayed much below the measured 66% peak and cover. This difference suggests that the model's default approach could not capture the sparse but persistent ground cover observed in the field. One reason can be the way the model had to be calibrated to simulate the produced biomass more or less accurately. To achieve the low observed biomass in the Control, an unrealistically low Water Productivity (WP) value had to be used. WP in AquaCrop is a conservative parameter (normally around 33 g/m^2 for C4-crops like maize) that links transpiration to biomass production. The calibration process revealed that keeping the standard WP led to overestimation of biomass, even after adding fertility stress. WP for the Control therefore had to be reduced to 20 g/m^2 (a value more typical for C3 crops) to hit the measured biomass of 2.37 ton/ha.

This adjustment is a clear limitation because it deviates from AquaCrop's usual assumption of a crop-specific WP and indicates the model was pushed beyond its normal range to replicate the low biomass observed in the Control treatment. However, it is important to note that WP is not directly related to nutrient stress in AquaCrop. The low WP value was likely used to compensate for a mismatch between the observed biomass and the simulated canopy development, particularly under nutrient stress. This may indicate that either the field-measured biomass was slightly overestimated, or that canopy cover was underestimated – or possibly a combination of both. However, given the model's sensitivity to these parameters, it remains uncertain which variable contributed most to the need for this adjustment.

The timing of when the plants reached the maximum CC also differed between the treatments. As the CC data was only measured every two weeks, it was a bit unclear what date the crops actually reached their maximum CC. Initially, the plan was to use the same date of max CC(week 20- 140 days after sowing), but due to difficulties with reaching the measured biomass in the simulation for the Control, this was changed to week 18(126 days after sowing). This is also a weakness to the calibration, because this parameter is very crucial and effect the simulation output to a large extent. A specific date for when the maximum CC was reached would therefore have made the calibration more accurate.

There may be several reasons why the model matched final yield better than it did with canopy cover. One explanation could be the limited field data available for calibration. As mentioned, canopy cover was only measured at a few time points, and other important variables, like soil nitrogen levels, have not been measured in detail. Because of this, the calibration process focused mainly on matching final biomass and yield, rather than how the crop developed throughout the season. It is also possible that CC was measured differently in the field than how AquaCrop defines it. For example, if the measurements did not reflect how much of the ground was shaded when viewed from directly above, this could help explain the difference between observed and simulated canopy development.

Another factor is the difference in plant density between the treatments. The BC3F plots had about 60 740 plants per hectare, while the Control had only 40 987 plants per hectare. This was likely due to poorer germination and survival. These differences were included in the model, but variations in plant spacing can still affect how canopy cover develops in ways the model may not fully capture (Sangoi, 2001). For instance, the Control, which had fewer plants with wider spacing might have developed decent individual leaf area but still left much of the ground uncovered. This observation is supported by (Sangoi, 2001), which explains that maize is highly sensitive to plant density, and that lower densities often fail to ensure full canopy closure. For instance, the article describes how sparsely planted maize may produce relatively large individual leaves, but the wide spacing between plants results in insufficient ground cover. This is consistent with (Sangoi, 2001), who describes how lower plant density can lead to gaps in canopy cover despite large individual leave, something that was also observed in the Control plots of this study. The article also notes that limited canopy development reduces light interception efficiency, which can negatively impact biomass production and yield potential. These are effects that may not be fully captured by the model, even though total plant numbers were included.

The reduced canopy cover could leave the soil surface more exposed to direct sunlight, rainfall and wind and have several consequences as a result of this. Firstly, increased soil exposure may lead to increased soil evaporation, reducing the amount of water available for plant uptake (Allen et al., 1998). The bare soil is also more vulnerable to the impact of raindrops, which can lead to surface sealing and reduced infiltration (Horton, 1940). This could potentially increase surface runoff and soil erosion (Lal, 1998). The low canopy cover might also lead to higher soil temperatures, which could potentially affect microbial activity and nutrient cycling (Hatfield & Prueger, 2015). All these factors could impact overall soil water dynamics and plant performance, beyond what the model simulations might predict.

Root growth added another layer of complexity. Field observations showed that maize roots in these rainfed crops remained relatively shallow by the time of flowering, about 0.33 meters in the Control. This was reflected in the model, which used a maximum rooting depth of 0.35 meters. As mentioned in Chapter 2, maize roots can reach up to 2.5 meters, so these roots are considered the minimum (Raes & Van Gaelen, 2016). As a result, the simulated crop experienced strong water stress, especially during flowering, due to a dry period, because it could not access deeper moisture. This matches what likely happened in the field. However, if some roots in reality reached deeper layers that were not captured in the field measurements, the model might have overestimated the level of stress. If that would have been the case, other parameters in the model would have needed to be calibrated differently to match the measured biomass, as the rooting depth is a rather sensitive parameter.

The simulated soil water profile during flowering (Figure 12) for BC3F shows that most of the remaining moisture was stored deeper in the soil, while the upper layers, likely where most roots are active, were already drier. This likely limited water uptake and contributed to continued canopy expansion stress at a critical stage. Flowering is known to be very sensitive to water stress, and even moderate shortages can reduce yield significantly (Çakir, 2004). Although rainfall had occurred earlier, the combination of low moisture in the upper root zone and high evaporative demand may have caused stress. Similar situations have been described where crops struggle to access deeper water due to shallow rooting, especially under dry conditions (Khanthavong et al., 2021). This highlights that both root depth and timing of rainfall is important for understanding water stress in the treatments.

During the modeling process, it was initially assumed, based on the background data, that differences in biomass between treatments could be partially explained by variations in soil water retention. However, the statistical analysis described in “2.5 Soil Water Retention” revealed no significant difference in soil water holding capacity between treatments, and the same soil file was therefore used across all simulations. This indicated that water availability alone could not account for the observed variation in crop performance, and differences in soil fertility were instead suspected to be the primary driver.

As the aim of the project originally was to see the isolated effect of biochar alone, a soil fertility stress calibration was attempted in AquaCrop. The model does not simulate nutrient balances mechanistically, so fertility stress was tried represented indirectly using AquaCrop's built-in "stressed field" function in the crop folder. The reference field(BC3F) was then supposed to be compared to a fictional stressed field(BC3F-noF) which had a stress level applied to simulate a scenario with biochar only, excluding the effect of fertilizer. That said, this attempt did not reveal any successful results. This simulation was only possible to run, when the fertility stress was set to "near optimal" or "moderate".

To summarize, AquaCrop was able to simulate the final yield reasonably well after calibration, more for the BC3F than the Control, but had trouble representing accurate processes like canopy development. This answers the first research question: AquaCrop can reproduce observed field outcomes with careful calibration, but its ability is more limited under less optimal conditions. These limitations highlight the importance of using the model with caution in other settings. For future use, more calibration data, such as frequent canopy cover measurements and accurate information about nutrient availability, could improve model reliability. Additionally, ensuring that canopy data are reported in a format that is compatible with AquaCrop's internal growth routines is essential, as this strongly influences biomass and stress calculation. Because AquaCrop only simulate nutrient stress indirectly (Vanuytrecht et al., 2014), improvements to the simplified representation of nutrient stress in the model could further increase confidence in the simulation results, especially under low-input conditions.

4.2 Effect of Biochar and Fertilizer on Maize Growth and Yield

4.2.1 Maize Growth under Low Fertility (Control treatment)

The field results from this experiment demonstrated a stark contrast between low-input and amended plots, underscoring the critical role of soil fertility in this rainfed system. The Control treatment (no biochar or fertilizer) produced very low biomass (around 2.37 ton/ha), which is consistent with the meager yields often observed in smallholder maize systems under rainfed, nutrient-depleted conditions (Aramburu-Merlos et al., 2024). Such low productivity reflects multiple compounding stresses. Most importantly, the absence of fertilizer in the Control meant that nitrogen and phosphorus were severely limiting. This matches broader evidence that inadequate macronutrient supply is a primary cause of reduced maize yields in Sub-Saharan Africa (Kiboi et al., 2023).

The non-fertilization in the Control plot led to a sparse CC (peak around 66%), greatly reducing light interception and photosynthetic capacity. This nutrient-constrained growth was further exacerbated by climatic stress, a dry spell during the flower period, a critical phase for maize growth (NSW Department of Primary Industries, 2016). Water deficits during flowering is known to decrease biomass production for maize plants (Khan et al., 2022). Thus, the poor performance of the Control can be explained by a combined effect of low soil fertility and drought stress during a sensitive stage. These findings align with the study's background expectations: soils in this region are inherently low in fertility after years of continuous cultivation, and without amendments, the biomass remained near the commonly cited 2 ton/ha average for rainfed African maize (Aramburu-Merlos et al., 2024). This outcome reinforces that improving nutrient availability is essential for closing yield gaps.

4.2.2 Yield Response to Biochar-Fertilizer Treatment

In marked contrast, the treatment receiving both biochar and mineral fertilizer (BC3F) achieved substantially higher biomass and yield (7.37 ton/ha). Fertilizer application provided essential nutrients that supported enhanced crop growth, consistent with evidence showing that even moderate NPK(Nitrogen, Phosphorus, Potassium) inputs can substantially improve maize yields on degraded soils (Kiboi et al., 2023). The addition of biochar at 3 ton/ha could have further enhanced crop performance beyond what fertilizer alone might achieve, this is further discussed below. Although a direct "fertilizer-only" treatment was not separately tested in this thesis, literature suggests that biochar can enhance fertilizer effectiveness through improvements in soil physical properties and nutrient retention (Wang et al., 2023).

4.2.3 Biochar's Influence: Nutrient Efficiency or Water Retention?

In this study, the BC3F plots attained 95% canopy cover, indicating a dense and healthy crop stand. This may suggest more efficient water use in the BC3F treatment, potentially linked to improved soil conditions. Biochar is known to enhance soil structure and porosity, often increasing plant-available water (Liu, Zuolin et al., 2017; Razzaghi et al., 2020). Although no statistically significant differences in soil water retention were found between treatments, it is theoretically possible that biochar improved the distribution or availability of water within the root zone. The AquaCrop simulations support this idea, as the BC3F scenario experienced less water stress, suggesting that the crop may have utilized rainfall more effectively. One possible explanation is that biochar improved soil structure or root-soil contact, enhancing water accessibility in a way not fully captured by volumetric measurements. For instance, (Kätterer et al., 2022) observed improved maize yields with modest biochar applications in Kenya, and suggested that improved plant-available water could be one contributing factor. While such mechanisms could be at play here, the statistical analysis showed no significant differences in measured soil water content. Therefore, it is not possible to conclude, based on this study alone, that biochar increased water retention, though it may have influenced water availability at a finer scale not detected by the applied methods.

Critically, the magnitude of biomass and yield improvement in BC3F suggests that fertilizer was the dominant driver, with biochar providing secondary benefits. This is consistent with meta-analysis showing that biochar alone often yields only modest crop response (on average 10% yield increase without added nutrients) (Jeffery et al., 2011). In this case, the most immediate contribution of biochar was likely improving fertilizer use efficiency. Studies under high fertility also report relatively small incremental gains from biochar; for instance, (Wang et al., 2023), found that even 15–45 ton/ha of biochar with ample N-fertilizer raised maize yields by only 5–10%.

The fourfold biomass increase that was observed from the Control to BC3F highlights how severe the initial nutrient limitation was. Based on background literature, biochar may have contributed to realizing the full benefit of these nutrients by improving soil chemical properties, for example by increasing pH and cation exchange capacity, which can enhance phosphorus availability (Hailegnaw et al., 2019; Liu, Zunqi et al., 2017; Martinsen et al., 2014). . However, these mechanisms were not directly measured in this study, and the water balance output showed no clear differences between treatments in infiltration, runoff, or deep drainage (Table 6), suggesting that biochar did not significantly alter water movement or leaching dynamics under the conditions of this experiment. Nonetheless, the results support the broader idea that integrating organic amendments like biochar with mineral fertilizer can enhance yield responses. This is consistent with findings by (Kiboi et al., 2023), who emphasize that combining organic and inorganic inputs improves nutrient use efficiency and supports more resilient cropping systems in smallholder agriculture.

While not directly measured in this study, the use of biochar could over time contribute to improved soil structure and organic matter content, supporting longer-term sustainability goals (Shyam et al., 2025; Voruganti, 2023). However, one must also consider economic and practical constraints. Biochar, while possibly beneficial, can be costly or labor-intensive to produce and apply at scale. For example, (Holt et al., 2022) found only minor short-term effects of biochar on yield, water availability, and crop quality, suggesting limited benefits under some conditions. Given these modest outcomes, biochar may not be cost-effective without financial incentives or long-term soil improvement goals. Overall, these results are promising for soil improvement strategies. However, they also highlight what the literature stresses: the use of biochar will depend on local cost-benefit conditions and the resources available to farmers (Campion et al., 2023). In short, the strong improvement in maize growth with the biochar and fertilizer treatment shows how combining soil amendments in a conservation agriculture system can help overcome input limitations, which is an important step toward closing yield gaps on smallholder farms.

4.3 Impact of Sowing Date on Simulated Biomass and Yield

As one of the final components of this research, it was explored how altering the planting by a few days earlier or later might influence maize performance, using the calibrated AquaCrop model for scenario simulations. This analysis was partly motivated by the high variability in rainfall in the region and the critical role of planting time in rainfed agricultural systems (Ngetich et al., 2011). Even small shifts in sowing date can determine whether a crop's critical growth stages align with periods of ample moisture or coincide with dry spells. In this simulation, this sort of analysis was conducted on the high input treatment, BC3F, to assess potential crop gains. Sowing 3, 7, 10 and 13 days earlier than 14th of April was tested, as well as 3, 7, 10 and 13 days after. The resulting trends provided insight into the sensitivity of yield to planting timing under the 2024 season conditions. The changed sowing date simulation suggest that early sowing may reduce water stress and improve biomass accumulation and yield in this system. The increase in stomatal closure and early senescence under later sowing scenarios likely reflects exposure to less favorable moisture conditions during key growth stages. This aligns with previous findings from Kenya that emphasize the importance of sowing date in semi-arid and tropical rainfed systems (Ngetich et al., 2011). While this analysis was model-based, it provides valuable insight into the timing sensitivity of the BC3F treatment under the given climate scenario.

Despite the promising results from the adjusted sowing date simulations, practical implementation among smallholder farmers will depend on their willingness to adopt such changes. The adoption decisions are often influenced by farmers perception of the risk and uncertainty of the outcome, especially in regions where agriculture is highly climate sensitive (Meijer et al., 2015). Even if models suggest yield improvements from earlier planting, farmers may be reluctant to shift practices without consistent evidence across multiple seasons. Since this analysis was based on a single season (2024), it remains unclear whether similar benefits would occur under different climatic conditions. This raises the broader issue of climate variability and change, and how traditional sowing calendars may no longer align with optimal rainfall patterns (Rurinda et al., 2015). In the future, changes in rainfall patterns may require farmers to adjust planting dates. While models like AquaCrop can guide these decisions, real-world testing is needed. Combining model results with local knowledge and good advisory services will be key to help farmers adapt to a changing climate (Adger et al., 2005).

4.4 Limitations and Uncertainties

4.4.1 Missing Biochar Only Treatment

This study specifically looked at a combined treatment (biochar plus fertilizer) versus an unfertilized Control, which reflected the available data. One gap in this study is the absence of a biochar-only treatment scenario. This means, it was not quantified the effect of biochar on maize production alone, without any mineral fertilizer, as the complete data sets were not available for this treatment. As noted in Section 4.2, literature suggests that biochar by itself can improve yields, but often to a lesser extent than when paired with nutrient inputs. For instance, a meta-analysis by (Jeffery et al., 2011) reported about a 10% average increase in crop yield from biochar application without added fertilizer. Field studies in SSA support this, such as (Kätterer et al., 2022), who observed maize yield gains from biochar in unfertilized plots. In the region of this study, where soils are degraded, it is reasonable to expect that biochar-only application could provide some improvement to crop production.

The absence of a biochar-only treatment limits understanding of biochar's independent contribution to yield. AquaCrop calibrations included only the combined treatment, so the isolated biochar effect was not determined. A hypothetical simulation without fertilizer in the BC3F scenario could provide insights, but it would rely on assumptions (e.g. nutrient vs. non-nutrient effects). Ideally, field data for biochar-only treatments would enable model calibration and improve accuracy. For now, literature suggests a 3 t/ha biochar application on poor soils could modestly increase yield, which, while smaller than fertilizer-driven gains, may still be agronomically relevant if paired with soil health benefits. Future experiments should include biochar-only treatments, or leverage existing long-term trials, such as those by (Jeffery et al., 2011) to validate the model for this scenario. This would enhance conclusions on biochar's independent effects and inform appropriate AquaCrop parameterization.

4.4.2 Climate and Weather Data Uncertainty

The reliability of this simulation results is directly tied to the quality of the weather data used. It relies on NASA POWER weather data for driving AquaCrop, which provides a convenient source of daily weather estimates for locations like Embu. However, this gridded dataset has limitations that introduce some uncertainties. NASA POWER data were retrieved from satellites and may not capture local microclimates. The satellites may not fully capture e.g. orographic rainfall patterns on the slopes of Mount Kenya or short term extreme events with perfect accuracy (Faccin et al., 2024; Kisaka et al., 2015; NASA POWER Project, 2024). This was especially noticed when local knowledge suspected that it was very unlikely that it rained every day during the growing season. However, even though there was not performed any calibration with ground stations, it was compared with a local station, and it did not show any significant differences. In general, crop models are highly sensitive to rainfall and temperature inputs (Berhane & Kefale, 2018). The AquaCrop simulations showed this, and even the simple sensitivity analysis that set all days with rainfall less than 1 mm to 0, showed a difference in output biomass. Even though this analysis showed little difference in biomass output, it is still important to take these kind of uncertainties into consideration while performing simulations like this.

Another thing that needs to be addressed is that this study considered only one season with its specific weather patterns(2024). Yield in rainfed systems is strongly influenced by the annual rainfall variability (Rurinda et al., 2015). Results from one single season, even if captured accurately, does not guarantee similar results under different weather. A limitation of this study is the lack of a multi-scenario or multi-year climate analysis. Running AquaCrop with historical weather or generated scenarios could provide yield ranges and improve realism. While this was beyond the scope here, it is recommended for future work.

4.4.3 Data Uncertainties

As mentioned in Chapter 2: Materials and Methods, the field and lab data used in this study was not measured by the author. While these measurements provided essential input for model calibration and evaluation, it is important to acknowledge that the data may not have been collected with AquaCrop's specific requirements in mind. The model relies on particular formats, timing, and types of measurements, especially regarding canopy development and rooting depth, that may differ from standard agronomic protocols used in the field. As a result, some differences between simulated and observed values could stem not from model weaknesses alone, but also mismatches between how variables were measured and how the model interprets them. This does not necessarily imply any fault in the field work itself, but rather highlights the importance of aligning data collection protocols with assumptions and structure of the simulation model being used.

4.5 Further Implications for Biochar and Crop Growth Simulation

The collective findings of this study carry several implications for conservation agriculture and sustainable land management in rainfed smallholder systems. First, the dramatic yield gains achieved by combining organic (biochar) and inorganic (fertilizer) inputs highlight the value of integrated soil fertility management, a core principle for sustainable intensification. Conservation agriculture traditionally emphasizes minimal soil disturbance, residue retention, and crop rotation. These results suggest that amending the soil can be a powerful complementary strategy to these principles. By improving soil structure and nutrient availability, biochar can help make CA more effective. However, its impact depends on nutrient supply and may be small if used alone. Also, the effects may take time to appear, especially at low application rates. Large-scale use of biochar also involves practical and financial challenges. Producing and applying biochar can be costly and labor-intensive, so its use needs to be considered in light of local conditions and resources. Crop models like AquaCrop can help explore the effects of these practices, but the model show clear limits under nutrient-poor conditions. Improving how models simulate soil fertility and organic amendments is important for making them more useful in CA-based farming systems.

Chapter 5: Conclusion

By addressing the original research questions, this study shows that applying 3 tons of biochar per hectare along with mineral fertilizer, significantly increased maize yields in nutrient-poor soils. The main driver behind this effect was most likely improved nutrient availability, which reduced nutrient stress and enhanced plant growth. Statistical analysis revealed that biochar alone did not improve crop growth by increasing soil water retention in this study. However, when used as part of a broader fertility strategy, biochar could have improved yields by supporting nutrient supply and improving overall soil quality. The AquaCrop model, after calibration, was able to closely reproduce the observed biomass values for both treatments, but struggled to accurately simulate canopy cover. Additionally, changing the plants sowing date in AquaCrop simulations showed potential to yield increasement under the 2024 season's climate. This indicates that good timing in crop management could help improve yields under rainfed conditions. However, such changes must be evaluated across various seasons, as well as weighed against production costs to assess their practical feasibility and long term benefits.

For future research, both field experiments and crop growth models, should continue exploring how to use biochar effectively together with other farming inputs to boost crop yields and improve soil health in sub-Saharan Africa. The findings from this study support that combining organic amendments like biochar with appropriate fertilization could be a promising strategy to sustainably increase food production and improve climate resilience in smallholder systems.

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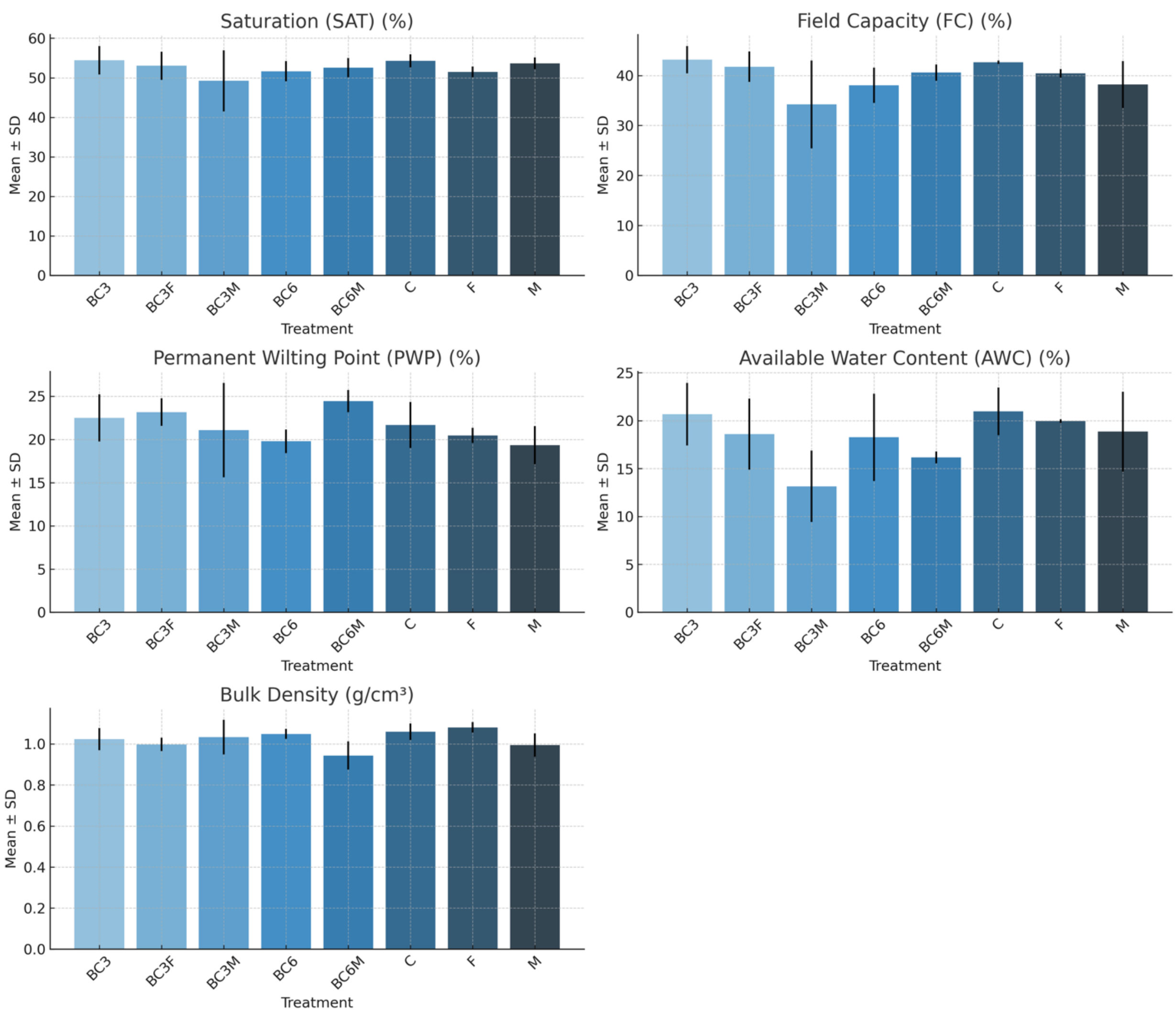
Chapter 7: Appendix

Appendix 1. Mean and standard deviation used for statistical analysis for BC3F treatment and Control

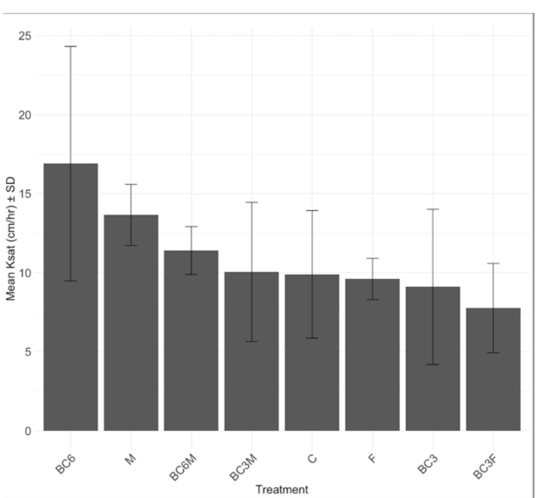
Treatment	SAT	FC	1	3	5	10	PWP	AWC	BD	Ksat (mm/day)
BC3F: Mean	53,02	41,76	28,98	26,52	25,44	24,03	23,16	18,60	1,00	1785.10
BC3F: Standard deviation	3,55	3,06	1,18	1,16	1,38	1,62	1,60	3,71	0,03	1,42
C: Mean	54,29	42,66	28,01	25,27	24,12	22,52	21,67	20,99	1,06	2257.41
C: Standard deviation	1,64	0,34	2,41	2,33	2,51	2,63	2,66	2,49	0,04	1,46

Appendix 2. Results from simulations for BC3F with changed sowing dates

Simulation Timing	Simulation date	Biomass (ton/ha)	Yield (ton/ha)	Avg. Canopy Expansion Stress	Avg. Stomatal Closure	Avg. Early Senescence
13 days before	1st of April	8,210	3,574	50 %	67 %	29 %
10 days before	4th of April	7,737	3,369	51%	67%	32%
7 days before	7th of April	7,496	3,263	51%	69%	34%
3 days before	11th of April	7,458	3,247	50%	75%	43%
Sowing date	**14th of April**	**7,480**	**3,257**	**49 %**	**79 %**	**48 %**
3 days after	17th of April	7,452	3,224	48%	83%	53%
7 days after	21st of April	7,326	3,189	47%	87%	64%
10 days after	24th of April	7,096	3,089	47%	89%	63%
13 days later	27th of April	6,698	2,916	48 %	87 %	62 %



Appendix 3: Variation in key soil physical properties across treatments.



Appendix 4: Statistical results of Ksat across treatments in the experiment.

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