BINDURA UNIVERSITY OF SCIENCE EDUCATION

FACULTY OF AGRICULTURE AND ENVIRONMENTAL SCIENCE

DEPARTMENT OF CROP SCIENCE

Evaluating Sorghum Yield Performance under Different Agronomic Practices and Rooting Depths using Long-Term Climate Data and FAO's AquaCrop Model



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DECLARATION

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FACULTY OF AGRICULTURE AND ENVIRONMENTAL SCIENCE

The undersigned hereby certify that they have examined and recommend this work for consideration by The Department of Crop Science, this project entitled:

Evaluating Sorghum Yield Performance under Different Agronomic Practices and Rooting Depths using Long-Term Climate Data and FAO's AquaCrop Model

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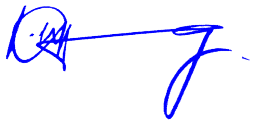

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Chairperson……

Date……

DEDICATION

I dedicate this work to my family.

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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is an important crop for food security in semi-arid sub-Saharan Africa. However, in Mbire District in semi-arid Zimbabwe smallholder farmers obtain sorghum yields in the range 0.20–0.60 t/ha against a genetic potential of 6.0 t/ha often leading to perennial food insecurity. This necessitates development of strategies to bridge the substantial yield gap between the potential and observed yields. The objective of this study was to evaluate sorghum yield performance under different agronomic practices and rooting depths using 44 years of seasonal climate data (1981/82–2024/25) and FAO's AquaCrop model. The study was conducted Mbire District. Daily climate data were obtained from NASA Power website, while crop data (planting dates, plant densities, and maximum effective rooting depth (ERD)) were collected through field measurements, questionnaires, and phenological observations. Soil samples were collected 0.15 m depth increments up to 0.60 m at 16 sites and analyzed for texture and pH using the hydrometer method and 0.1 M calcium chloride method, respectively. AquaCrop model was calibrated with local parameters including an adjusted water productivity of 30.7 g/m² and reduced emergence time from 13 to 6 days. Data analysis was performed using IBM SPSS Version 20.0. Shapiro-Wilk's test for normality showed that crop yield data was not normally distributed ($P < 0.05$), therefore non–parametric tests were applied: Spearman's rank correlation for rainfall-yield relationships, Wilcoxon Signed-Rank test for comparing simulated and observed yields, and Friedman test with Bonferroni correction for determining effect of planting date, plant density, and maximum ERD on sorghum yield. Results showed a moderate positive relationship between seasonal rainfall and sorghum yield. A substantial yield gap was revealed between simulated potential yields and observed yields. Planting date significantly influenced yields, with the first and second planting dates producing yields 1.31 times higher than the third. Plant density significantly affected yields, with maximum yields at 75,000 plants/ha, while maximum ERD improved yields by 18.2%, 35.5%, and 14.6% as rooting depth increased from 0.30 to 0.45 m, 0.30 to 0.60 m and 0.45 m to 0.60 m respectively. The study recommended the following for increasing sorghum yield: breaking root growth restricting layers, selecting deep rooting cultivars, and early planting, and plant densities between 45,000 and 75,000 plants/ha. Experimental research was recommended to test recommendations from this study.

Keywords: AquaCrop model, Plant density, Planting date, Rainfed cropping, Rooting depth, Sorghum yield.

Table of Contents

DECLARATION ii
ACKNOWLEDGEMENT iv
ABSTRACT v
LIST OF ACRONYMS AND ABBREVIATIONS viii
LIST OF TABLES ix
LIST OF FIGURES x
CHAPTER 1: INTRODUCTION 1
1.1 Background 1
1.2 Problem Statement 2
1.3 Justification 2
1.4 Objectives 3
1.4.1 Main Objective 3
1.4 2 Specific Objectives 3
1.5 Hypothesess 3
CHAPTER 2: LITERATURE REVIEW 4
2.1 Origin, Taxonomy and Botanical Description of Sorghum 4
2.2 Importance of Sorghum 4
2.3 Climatic and Soil Requirements 5
2.4 Biophysical Factors Affecting Sorghum Yield 6
2.5 Relationship between Seasonal Rainfall and Sorghum Yield 7
2.6| Effect of Maximum Effective Rooting Depth on Sorghum Yield 8
2.7 The AquaCrop Model: Principles and Applications 9
CHAPTER 3: MATERIALS AND METHODS 11
3.1 Study Area 11
3.1.2 Soils, Vegetation and Landuse 11
3.2 Selection of Study Site 11
3.3 Agronomic Practices 12
3.4 Data Collection 12
3.4.1 Climate data 12
3.4.2 Crop data 12
3.4.3 Field management 13
3.4.4 Soil data 13
3.4.5 Sorghum Genotypes 14
3.5 AquaCrop Model Description 14

3.6 Model Input Data and Parameters 14
3.6.1 Climate data 14
3.6.2 Crop growth and development parameters 14
3.6.3 Soil data 15
3.6.4 Field management 16
3.6 Evaluation of AquaCrop Performance 16
3.7 Definitions and Background Information 17
3.7. 1 Data Analysis 17
4.1Soil and Crop Data 19
4.2 Seasonal Rainfall and Reference Evapotranspiration (ETo) 19
4.3 AquaCrop Model Performances 20
4.4 Relationship of Crop Yields and Seasonal Rainfall 20
4.5 Comparison between Actual and Simulated Sorghum Yields 20
4.6 The effect of planting dates on sorghum yield 20
4.7 The effect of plant density on sorghum yield 21
4.8 The effect of maximum ERD on sorghum yield 22
5.1 Soil type, Seasonal Rainfall and Reference Evapotranspiration 23
5.2 Relationship between Sorghum Yield and Seasonal Rainfall 23
5.3 Comparison between Observed and Simulated Sorghum Yields 23
5.4 Effect of Planting Date on Sorghum Yield 24
5.5 Effect of Plant Density on Sorghum Yield 25
5.6 Effect of Maximum ERD on Sorghum Yield 25
6. 1 Conclusion 27
6.2.1 Recommendations for Practice 28
6.2.2 Recommendations for Research 28
REFERENCES 29

LIST OF ACRONYMS AND ABBREVIATIONS

ARDAS	Department of Agricultural and Rural Development Services
CAMPFIRE	Communal Areas Management Programme For Indigenous Resources
CV	Coefficient of Variation
ENSO	El Niño-Southern Oscillation
ERD	Effective Rooting Depth
FAO	Food and Agriculture Organization of the United Nations
MSD	Meteorological Services Department
PSII	Photosystem II
SD	Standard Deviation
SSA	Sub-Saharan Africa

LIST OF TABLES

Table 1. Effect of plant density on sorghum yield

LIST OF FIGURES

Figure 1. Total rainfall and reference evapotranspiration trends for 1981/82–2024/25 seasons at Mushumbi Pools in Zimbabwe

Figure 2. Variation of sorghum yield with planting date (Error bars represent standard deviations)

Figure 3. Effect of maximum effective -rooting depth on sorghum grain yield (Error bars represent standard deviations)

CHAPTER 1: INTRODUCTION

1.1 Background

Crop production in Sub Saharan Africa (SSA) is highly vulnerable to climate change and variability, because more than 95% of farmers depend entirely on rainfed agriculture (Omokpariola *et al*., 2025). The situation is more severe in arid areas, which cover approximately 18% of the total land area of (FAO, 2002). Climate change adds another layer of vulnerability because it increases incidence of drought, exacerbates soil degradation, and increases resource scarcity (Rathore, 2024). As a result of the adverse conditions hunger affects over 20% of Africa's population, compared to less than 10% in Asia and Latin America.

In Southern Africa, climate projections indicate warmer temperatures and decreased rainfall during the 21st century (Hamadjoda Lefe *et al*., 2024). Even in Zimbabwe, where seasonal rainfall totals has shown insignificant change, rising temperatures and high evaporative demand dry soils faster and intensify crop water stress. Additionally, heat waves, which severely reduce crop yields, are becoming more frequent but remain poorly documented in agro climatic research (Bouhenache *et al*., 2025). Adverse climatic conditions have led to calls for adoption of adaptation strategies that include cultivation of drought tolerant crops (Wakweya, 2023).

Sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most important cereal globally (Nyoni *et al*., 2020) and the second most important cereal in the dry regions of SSA (Kazungu *et al*., 2023). In the Southern African Development Community, sorghum and millets account for 23 % of cereal production, and in Zimbabwe sorghum is specifically recommended for semi-arid communal lands, which constitute 74 % of the farming area (Silas et al., 2021). The crop tolerates both drought and waterlogging, reflecting dual adaptation to moisture extremes (Wu & Bose, 2024). However, despite its inherent resilience, increased incidence of drought related sorghum failure has been observed in semi-arid Zimbabwe (Kubiku *et al*., 2022).

Sorghum failure occurs due to dry spells of 10–14 days during flowering (Ndlovu *et al*., 2021), rising temperatures that dry soils faster, these adverse climatic conditions are experienced during the El Niño seasons (Furtak & Wolińska, 2023). Besides the adverse climatic conditions, smallholder farmers often plant late, using low plant densities and without enough fertilizer thereby reducing sorghum yields by 40–68% in West Africa. Delayed planting in South Africa reduced yields from over 3 t/ha to 0.43 t/ha (Touch *et al*., 2024). In Zimbabwe, average sorghum yields are in the range of 0.25–0.30 t/ha against a genetic potential of 7.0 t/ha (Nathan &

Sebastian, 2026). With 80% of farmers in semi-arid regions being resource poor smallholders, they have little room to adapt (Lowder *et al*., 2025).

It is difficult for the farmers to know the best planting window and assess effect of plant density and rooting depth particularly in dry seasons, because most trials run over one to two years only. Crop growth models provide a viable option for evaluating agronomic practices over a longer term through scenario simulation using historical climate.

1.2 Problem Statement

Mbire District faces chronic food insecurity, where 64.7% rely on direct government food aid relative to 15% at national level (Mashizha & Tirivangasi, 2025). The food insecurity, which is often coupled with low household income, is due to low crop yields including that of the recommended drought tolerant crops. Sorghum yields are in the range 0.20–0.60 t/ha due to erratic rainfall and suboptimal, agronomic practices. Consequences include 27% child stunting (UNICEF), school dropouts, and high government expenditure on relief costs. This study applies AquaCrop to evaluate effect of planting date, plant density, and maximum ERD on sorghum yields in Mbire District in order to develop evidence based strategies of improving crop yields.

1.3 Justification

Sorghum is an important staple food crop in semi-arid Zimbabwe including Mbire District; therefore, its production has a direct bearing on food security in these areas. Besides, its socio-economic significance, the study will contribute to the body of knowledge on sorghum production. Specifically the study will quantify sensitivity of sorghum yield to planting dates, maximum ERD and plant density. Information generated in this study will help extension officer in advising farmers. Farmers will benefit from increased yields that will lead to household food security and improved income. Zimbabwe government will benefit from the information that is critical for decision making and savings in expenditure incurred in mobilizing food aid if recommendations from the study improve crop yields. Therefore, this research contributes towards shifting the approach from costly emergency food aid to proactive, science based adaptation that benefits all actors and stakeholders along the sorghum value chain.

1.4 Objectives

1.4.1 Main Objective

The main objective of the study was to evaluate sorghum yield performance under different agronomic practices and rooting depths using long-term climate data and FAO's AquaCrop model.

1.4 2 Specific Objectives

The specific objectives of the study are to:

1.4.2.1 determine the relationship between long term crop yields and total season rainfall;

1.4.2.2. compare crop yields simulated using FAO's AquaCrop with crop yields achieved by farmers in the study area;

1.4.2.3 determine the effect of planting dates on sorghum yield;

1.4.2.4 determine the effect of plant density on sorghum yield; and

1.4.2.5 determine the effect of maximum ERD on sorghum yield.

1.5 Hypothesess

H_o: There is no significant relationship between sorghum yields and total seasonal rainfall.

H_o: There is no significant difference between sorghum yields simulated by AquaCrop and yields achieved by farmers in the study area.

H_o: There are no significant differences in yields for different planting.

H_o: There are no significant differences in yields among different planting densities.

H_o: There are no significant differences in yields among different maximum ERDs.

CHAPTER 2: LITERATURE REVIEW

2.1 Origin, Taxonomy and Botanical Description of Sorghum

Sorghum is an ancient cereal crop that ranks as the fifth most important cereal globally after rice *Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize *(Zea mays* L.), and barley (*Hordeum vulgare* L.), occupying approximately 40 to 50 million hectares of land annually with a global grain production of up to 60 million metric tons (Mundia *et al*., 2019). The crop has historically served as a major staple food source, and its importance extends beyond food to include feed, fuel, forage, and industrial applications such as ethanol production. Botanically, sorghum is a member of the tribe Andropogoneae within the grass family (Poaceae) the same tribe that includes other important crops like sugarcane *Saccharum officinarum* L.) and maize. The genus sorghum is diverse, comprising about 25 species that are further grouped into five subgenera: Chaetosorghum, Heterosorghum, Parasorghum, Stiposorghum and Eusorghum (Ananda *et al*., 2020). Among these, some species have been domesticated and cultivated as cereals for human consumption or as pastures for livestock, while others remain wild or weedy. The most agriculturally important species is *S. bicolor,* which encompasses the vast majority of cultivated sorghums grown globally. This species falls within the subgenus Eusorghum, which also contains several wild relatives. Based on differences in flower and panicle morphology, *S. bicolor* has been further classified into five major races: Bicolor, Guinea, Caudatum, Kafir, and Durra (Andrews *et al*., 2019).

2.2 Importance of Sorghum

Sorghum is one of the world's most underappreciated crops, yet its importance to millions of people cannot be overstated. In the hot, dry, and marginal farming regions of SSA and South Asia, sorghum is a lifeline (Khalifa & Eltahir, 2023). While maize, wheat, and rice may fail when rains become scarce, sorghum endures. It survives on as little as 250 to 400 mm total seasonal rainfall.

Sorghum grain is rich in complex carbohydrates, dietary fibre, and essential minerals such as iron, zinc, magnesium, and phosphorus. It contains B vitamins and, in colored varieties, powerful antioxidants called phenolic compounds and 3-deoxyanthocyanins rare in other cereals. Sorghum is naturally gluten free, making it a safe and healthy alternative for people with celiac disease. Its low glycaemic index helps manage blood sugar levels, which is increasingly valuable as diabetes

rises even in developing countries (Tanwar *et al*., 2023). Sorghum porridge provides sustained energy and is easy to digest when properly processed.

Economically, sorghum supports the livelihoods of hundreds of millions of smallholder farmers. In semi-arid regions where cash crops struggle, farmers can sell surplus sorghum at local markets or to government marketing boards, generating income for school fees, medicine, and other basic needs.

In this an era of climate change, sorghum's importance is growing. Rising temperatures, erratic rainfall, and more frequent droughts are making conventional cereals increasingly risky. Sorghum, with its deep root system and waxy leaves that reduce water loss, thrives where maize fails. It can also withstand temporary water logging and extreme heat above 40°C (Behera *et al*., 2022). By incorporating sorghum into their cropping systems, farmers can reduce their vulnerability to climate shocks. Governments and development agencies now promote sorghum as a climate-smart crop that builds resilience.

Industrially, sorghum is remarkably versatile. Sweet sorghum varieties provide fermentable sugars for bioethanol production. The fibrous residue can be used for building materials or burned for electricity. Sorghum stalks serve as animal fodder and silage, while the grain brews traditional and commercial beers. Even the dried stalks find use as roofing and fencing materials in rural areas.

2.3 Climatic and Soil Requirements

Sorghum thrives in warm, hot climates and is best suited to tropical and subtropical regions. The optimal temperature for growth ranges from 25 to 35°C, with germination requiring a minimum temperature of 7°C to 10°C and 80% of seeds germinating within 10 to 12 days at 15°C (Hossain *et al*., 2022). Temperatures below 15°C or exceeding 40°C can negatively affect growth and reduce yields, while frost is particularly harmful to the crop (Devi *et al*., 2023). Under optimal growing conditions, a frost-free period of approximately 120 to 140 days is required for the crop to reach maturity and high production. Crop water requirements (evapotranspiration) for a 110 to 130 day sorghum variety range from 450 to 650 mm depending on climatic conditions (Soni *et al*., 2025). Sorghum exhibits considerable flexibility in its water requirements, with optimal annual rainfall ranging from 500 mm to 1,000 mm, although the crop can survive on as little as 250 mm to 400 mm in drier regions (Assefa *et al*., 2010).

Regarding soil requirements, sorghum demonstrates remarkable adaptability and can be grown on a wide variety of soil types, including marginal soils with low fertility. Sorghum prefers soils deep, well drained, fertile soils with clay content between 10% and 30% and fairly consistent rainfall throughout the growing season for maximize yields (Masaka *et al*., 2021). The crop grows in soils with a pH range of 5.5 to 8.5 and it is fairly tolerant to alkalinity and salinity, enabling it to be grown on soils that would be unsuitable for other grain crops. Excessive moisture and prolonged drought are both harmful to sorghum, and waterlogging can severely reduce yields (Zhang *et al*., 2025). Soils with moderate fertility levels are acceptable for sorghum production, although optimal yields are achieved on soils with adequate nutrient availability and good drainage characteristics. The crop's ability to survive and produce good yields on minimal water, combined with its tolerance of harsh soil conditions, makes it an excellent choice for farmers in arid regions or areas with limited rainfall, particularly in the context of climate change.

2.4 Biophysical Factors Affecting Sorghum Yield

Sorghum production is constrained by an array of biophysical factors that collectively determine the final yield. Drought stress is the most significant factor limiting sorghum productivity, primarily by restricting water availability during critical growth stages. Drought significantly reduces sorghum productivity by limiting water availability, affecting grain yield and biomass through reduced photosynthetic efficiency, dehydration, osmotic stress and reduced nutrient uptake. Climate related problems such as extreme temperature, erratic rainfall patterns, soil degradation, heat waves, flooding, waterlogging, pests and diseases all afflict the production and sustainability of sorghum globally (Kushwaha & Kamalvanshi, 2023). The interaction of multiple stresses often compounds the negative effects, with drought and high temperature stress occurring simultaneously in many sorghum growing regions.

Pests and diseases represent another major constraint to sorghum production. Grain sorghum yield has been found to be negatively correlated with canopy infrared temperature, green bugs (*Schizaphis graminum* (Rondani)), corn leaf aphid (*Rhopalosiphum maidis* (Fitch, 1856)), and maize dwarf mosaic virus (*Potyvirus zeananus)*. Major sorghum diseases are caused by fungal pathogens such as anthracnose (*Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc.), grain mold (*Fusarium verticillioides* (Sacc.) Nirenberg) and rust (*Puccinia graminis* Pers.), while insect pests including sorghum midge (*Contarinia sorghicola* (Coquillett, 1899)), stem borers (*Chilo partellus* (Swinhoe, 1885)), shoot fly (*Atherigona soccata* Rondani, 1871) and aphids

(*Melanaphis sacchari* (Zehntner, 1897)) cause substantial yield losses annually. Insect attacks can provoke more severe plant water stress and greater yield loss than non-irrigation alone. Climate change is expected to exacerbate these pressures, as rising temperatures may expand the geographic range of many pests and pathogens.

In addition, soil degradation and nutrient depletion significantly constrain sorghum yields, particularly in smallholder farming systems where access to fertilizers is limited. Water deficit during the mid-season and late season growth stages has been identified as a major constraint, often causing substantial yield losses across eastern and southern Africa. Weeds also pose a serious threat to sorghum production, competing aggressively with the crop for water, nutrients and light. Planting density has been identified as a key factor in reducing sorghum productivity, with yield reductions of up to 68% attributed to suboptimal plant populations in some agro-ecological zones (Adam *et al*., 2022). Despite these numerous constraints, sorghum exhibits significant genetic diversity, providing a rich resource for breeding programs aimed at developing improved varieties with traits such as higher yield, disease resistance, and enhanced nutritional quality.

2.5 Relationship between Seasonal Rainfall and Sorghum Yield

Intra seasonal rainfall characteristics such as the number of rainy days, which is mainly determined by rainy season duration, and the occurrence of long dry spells have been shown to strongly influence final sorghum yields (Pamalba Narcise *et al*., 2023). Studies have demonstrated that seasonal rainfall, amount of soil evaporation, crop transpired water, and ground canopy cover are key parameters influencing sorghum biomass, yield and water productivity (Wang *et al*., 2022). High rainfall amounts that are poorly distributed can paradoxically result in high soil evaporation, low transpiration and low crop yields when the rainfall exceeds the soil's infiltration capacity or is concentrated in heavy events that produce runoff.

Analysis of rainfall patterns in sorghum growing regions reveals that the timing and reliability of rainfall are as important as the total amount received. The vegetative phase has shown a strong positive correlation with rainfall, while the reproductive phase and maturity phase show progressively weaker correlations. Short rainy seasons receiving less than 300 mm of rainfall are generally insufficient for successful sorghum production, with studies showing that only 36.4% of long rainy season years produce high yields, 42.4% produce normal yields, and approximately 21% result in low or no productivity (Omay *et al*., 2023). Climate change projections indicate an

overall decline in precipitation across many sorghum growing regions accompanied by rising temperatures, which will likely reduce sorghum yields in the future unless effective adaptation strategies are implemented. Whilst there is evidence that rainfall affects sorghum yield, this has not been adequately studied in semi-arid Zimbabwe.

2.6| Effect of Maximum Effective Rooting Depth on Sorghum Yield

The rooting depth of sorghum plays a crucial role in determining crop productivity, particularly under water limited conditions. Sorghum possesses an exceptionally well developed root system with fine branches that enables the plant to access soil moisture at considerable depths, contributing significantly to its reputation as a drought tolerant crop. The deep roots of sorghum play a key role in yield production, although roots at different soil depths regulate yield production in different ways. Effective rooting depth is the soil depth from which a crop extracts most of its water and nutrients, typically where the majority of root mass is active. Research using root removal experiments has demonstrated that eliminating roots at 0.30 m depth and at 0.60 m depth significantly reduces yield in sorghum cultivars (Schmidt, 2014).

The contributions of roots below 0.30 m to the yield of sorghum hybrids were notably higher than those below 0.60 m, indicating that even moderately deep roots make substantial contributions to yield formation. Roots below 0.30 m significantly reduced the dry matter weights of leaves, stems, sheaths, and panicles, whereas 0.60 m only significantly reduced panicle dry matter weight. Moreover, 0.30 m significantly reduced photosynthetic levels and Photosystem II (PSII) reaction center activity. Although both root removal treatments reduced root activity and the concentrations of soluble sugars, amino acids, gibberellins and abscisic acid in root bleeding sap, several of these indicators of depth of 0.60 m were significantly higher than those in 0.30 m during the filling stage, suggesting that deeper roots have a critical regulatory effect on the physiological processes of aerial plant parts.

Deep roots deserve serious consideration as a potential trait for yield improvement, especially under drought conditions. Modeling studies have quantified the potential benefits of deeper rooting, with simulations showing that a hypothetical 1.20 m root depth sweet sorghum cultivar could achieve final biomass yields up to 48.2% higher than widely grown cultivars in rainfed systems, while requiring up to 32% less irrigation to meet actual evapotranspiration demand (Thorup-Kristensen *et al*., 2020). However, soil characteristics strongly influence the effectiveness of deep rooting. In Ultisol, sorghum plants were unable to effectively extract available soil moisture at depths below 0.45 m, resulting in reduced plant growth and grain yield

compared to Oxisol soils where deeper moisture extraction was possible. Effective rooting depth is therefore influenced by both genetic factors and soil physical properties, highlighting the need for integrated approaches to improve water uptake in rainfed sorghum production systems (Parwada *et al*., 2019).Whilst effective rooting depth is important in sorghum production, there are currently no documented studies on effective rooting depth in Zimbabwe.

2.7 The AquaCrop Model: Principles and Applications

AquaCrop is a crop growth simulation model developed by the Land and Water Division of the Food and Agriculture Organization (FAO) specifically designed to assess the effect of environment and management on crop production under water limiting conditions (Steduto *et al*., 2009). Unlike many other crop models that use complex leaf area index calculations, AquaCrop employs a "water-driven" growth engine that calculates above-ground biomass as a function of transpiration normalized via reference evapotranspiration (ETo) (Jahandideh *et al*., 2026). The model predicts attainable yield under water limiting conditions by simulating canopy development, stomata conductance, canopy senescence, and harvest index as the key physiological crop responses to water stress (Xu *et al*., 2021). Rootzone water content is simulated by keeping track of incoming and outgoing water fluxes at the boundaries of the soil profile, treating the soil as a water storage reservoir with multiple layers.

The model accommodates various fertility levels and water management systems, including rainfed, supplemental, deficit irrigation, and full irrigation regimes, making it applicable to a wide range of agricultural production systems (Vanuytrecht *et al*., 2014). AquaCrop serves multiple practical applications, including understanding crop responses to environmental change, comparing attainable and actual yields in fields and farms, formulating optimal irrigation schedules under water deficit conditions, assessing crop responses to environmental change, and developing irrigation strategies for both irrigated and rainfed agriculture. The model is particularly useful for extension services, farmer associations, irrigation districts, and policy analysts who require crop models for planning and assessing water needs at project and regional scales.

In sorghum production specifically, AquaCrop has been extensively validated and applied to address climate change impacts. Evaluation studies have demonstrated strong agreement between model simulations and observed values for seed yield, biomass, harvest index, and water use efficiency. The model has been successfully used to formulate optimal planting dates and best practice management recommendations for rainfed sorghum production under varying

agro-ecological conditions, identifying key parameters such as seasonal rainfall, soil evaporation, crop transpiration, and canopy cover as critical determinants of sorghum biomass, yield and water productivity (Hadebe *et al*., 2020). Applications of AquaCrop for sorghum have also included simulating the effects of biochar amendment on soil water storage and crop yields, as well as evaluating future climate change scenarios to predict yield declines and inform adaptation strategies for sorghum production systems in semi arid environments (Starr et al., 2020). The model is a valuable tool for researchers, extension agents, and policy makers seeking to enhance sorghum productivity and resilience in the face of climate variability and change.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location and Climate

The study was conducted in Mbire District in the Middle Zambezi Valley, in northern Zimbabwe approximately 16.17° S, 30.55° E at an average elevation of 356 m above sea level (a.s.l). The area lies in agroecological region Va, experiencing a dry tropical climate with a unimodal rainy season from November to March. The mean annual rainfall is ± 650 mm, with December to February (the peak growing season) coinciding with the maximum strength of the El Niño Southern Oscillation (ENSO). Mean annual temperature is 25 °C, exceeding 40 °C before the rains and dropping to around 10 °C in June–July (Asare-Nuamah & Amungwa, 2021).

3.1.2 Soils, Vegetation and Landuse

Soils range from fine grained loamy sands to sandy clays. Natural vegetation is savanna woodland, with riverine forests along the Angwa and Zambezi Rivers; common trees and shrubs include acacias and combretums, while native grasses such as *Hyparrhenia* and *Eragrostis* species are increasingly displaced by invasive *cassiatora* and pink morning flower (Chakuya & Ndebele, 2025). Land use is dominated by smallholder subsistence agriculture, with major rainfed cereals being maize, sorghum, and pearl millet (*Cenchrus americanus* (L.) Morrone), alongside sesame (*Sesamum indicum* L.), cotton (*Gossypium hirsutum* L.), and horticultural crops along riverbanks; livestock kept includes goats, cattle, pigs, and poultry, with wildlife management under the Communal Areas Management Programme for Indigenous Resources (CAMPFIRE) programme.

3.2 Selection of Study Site

The study site was purposively selected based on its representativeness of sorghum production systems under dry land conditions in northern Zimbabwe. All the 17 wards in the district targeted for the study in order have adequate coverage of different soil types and farming practices found across the district. However data for Ward 12 could not be collected due to logistical challenges. Questionnaire respondents were selected randomly from a list of sorghum growing households obtained from local agricultural extension officers. Soil samples were collected at points that were considered to be representative of soils in each ward with the aid of agricultural extension officers and sorghum lead farmers.

3.3 Agronomic Practices

Farmers use conventional tillage methods such as hand hoeing or animal drawn ploughs where available. Weed control is carried out using hand hoeing, usually two to three times per season; herbicide use is rare due to cost constraints. Fertilizer application is generally not practiced by farmers in the district because the unreliable and erratic rainfall makes any investment in fertilizer risky. Farmers cannot guarantee a return on their investment. Farmers also practice intercropping and some apply mulch in their fields.

Planting time is determined by the onset of the rainy season, with most farmers sowing after the first effective rains. Two official criteria are used to advise farmers on planting decisions. The first is the Department of Agricultural and Rural Development Services ARDAS criterion, which advises planting when cumulative rainfall exceeds 25 mm in seven days. The second is the Meteorological Services Department (MSD) criterion, which advises planting when cumulative rainfall reaches at least 40 mm in four days (Mupangwa *et al*., 2011) . Sorghum is planted in furrows made by the mould board plough with inter-row spacing ±0.9 0 m. Under this system the seed is sown by thinly spreading it in the furrow and latter thinned to the desired spacing. Some farmers plant in panting holes dug using a hand hoe at spacing of 0.9 m × 0.4 m. Under this practice farmers plant ±3 seeds per station giving approximately 83,000 plants/ha but the final crop stand is usually about half this number due to poor emergence.

3.4 Data Collection

3.4.1 Climate data

Daily climate data for Mushumbi Pools was obtained from the NASSA Power website, covering a 44-year period from the 1981/82 season through to 2024/25. This dataset provided the essential meteorological inputs for the crop growth modelling, including rainfall, temperature, relative humidity, and solar radiation.

3.4.2 Crop data

Crop data (plant density, planting date, growing cycle, and maximum ERD) was collected using a combination of methods. Plant density measurements were conducted in 10 m × 10 m plots by counting of all sorghum plants in each of four (4) representative sorghum growing fields. Data on planting date, days from planting to specific growth stages, and growing cycle was collected through interviews with 35 farmers. Planting date data used in crop growth modelling was

obtained by applying the ARDAS and MSD criteria to the seasonal rainfall for the period 19981/82 to 2024/25.

To track growing cycle and plant growth stages observations were recorded weekly at 3 selected plots throughout the entire season. During each visit, the researcher visually scored the crop using standard phenological keys recording stages like emergence, stem elongation, flag leaf, booting, flowering, grain filling, and physiological maturity which allowed us to determine the duration of each phase and the total cycle length.

Sorghum yield data from 1992/93 to 2024/25 was obtained from ARDAS at the Mbire District Offices. Maximum ERD the deepest layer where plants get most of their water was measured by digging pits around mature sorghum plants and recording the maximum depth of the roots (Han *et al*., 2025) in the same plots where plant density measurements were done. In the sandy and shallow soils typical of the area, roots often encounter hard layers or poor structure, so these measurements were essential for realistic model inputs.

3.4.3 Field management

Field management such as mulching, weed control, and soil fertility management was collected through a questionnaire survey and supplemented by field observations.

3.4.4 Soil data

Soil samples for soil texture and pH were measurements were collected in the 0–0.60 m layers at 16 representative sites spread across the district. At each site, sampling was executed using a stainless-steel soil auger to avoid metallic contamination. To capture depth wise variability within the root zone, samples were collected from at 0.15 m depth intervals 0–0.15 m, 0.15–30 m, 0.30–0.45m and 0.45–0.60 m at each location.

Five individual sub cores were taken from the corners and center, which were then thoroughly homogenized to form a single composite sample per depth interval. Consequently, a total of 48 composite samples (16 sites × 3 layers) were collected for laboratory analysis. Immediately following extraction, each composite sample was carefully sealed in pre labelled, heavy duty polyethylene zipper bags to prevent cross contamination and moisture loss. Soil pH was analyzed using the 0.1 M calcium chloride method. Soil particle size distribution was determined using the hydrometer method (Zhao & Naeth, 2024).

3.4.5 Sorghum Genotypes

The major sorghum genotypes grown in Mbire District are Marcia and SC SILA (Mukondwa et al., 2021). Both are open pollinated varieties (essentially improved landraces) that have been widely adopted because they are well suited to the harsh conditions of the Middle Zambezi Valley. They are dwarf types, reaching only about 1.5 m in height, which helps them avoid lodging and channel less photosynthesis into stems and more into grain. They mature in 120 days when grown below 800 m a.s.l, which fits neatly into the short rainy season. Farmers value them not only for their reliability but also for their medium tannin content, which gives some protection against birds, and their red seed color, which is preferred for local food uses.

3.5 AquaCrop Model Description

The AquaCrop model was chosen for this study because unlike more complex models that require many input parameters, AquaCrop strikes a practical balance between simplicity and accuracy. The model relates the amount of water used by a crop for biomass production to transpiration using the equation:

$$B = WP \times \Sigma Tr$$

where B is the cumulative aboveground biomass (in kg/m²),

Tr is transpiration (in mm), and WP is the water productivity parameter (kg of biomass per m² per mm of water transpired).

Crop yield (Y) is then obtained by multiplying B by a harvest index (HI), which represents the fraction of biomass allocated to the harvested grain. Simulations are run on a daily time step, using either thermal time growing degree days or calendar days. AquaCrop's ability to simulate sorghum yield has been tested in diverse environments around the world, including Sudan to the United States to South Africa, giving confidence that it can perform well in the semi-arid conditions of the Mid-Zambezi Valley.

3.6 Model Input Data and Parameters

3.6.1 Climate data

The daily climate data from NASA Power website were imported directly into AquaCrop. Reference evapotranspiration was calculated by the model's in-built ETo Calculator.

3.6.2 Crop growth and development parameters

Plant density, planting date, growing cycle, and maximum ERD were entered into the model by modifying the default sorghum file as part of a minimum data input calibration procedure (Djaman *et al*., 2022). According to Demissie et al. (2023) sorghum roots can grow up to 0.45 m, hence this depth was used in all simulations. Field measurements showed that roots penetrated on average to ±0.35 m, with considerable variation. I used a slightly lower depth of ±0.30 m in rooting depth scenario simulations. The time from sowing to emergence was reduced from the default 13 days to just 6 days. This adjustment reflects the high temperatures at low altitude Mushumbi Pools sits below 356 m and approximates four days cited by farmers.

Days to maturity in the default sorghum file is 102 days, which is less than the 120 days reported for Marcia and SC SILA when grown at 800 m altitude. Temperature decreases with altitude at about 6.5 °C per 1000 m (Montgomery, 2006). For most cereals including sorghum, 1 °C increase shortens the growing cycle by 5–7 days. At 356 m a.s.l., the estimated shortest maturity period is 105 days, which is close to the default days to maturity (102) days and maturity period observed in the field, therefore, I adopted the default days to maturity.

Planting dates based on both the ARDAS and MSD criteria were determined from climate data for each season as stated above. For plant density, the recommended minimum of 90,000 plants per hectare (Hatfield & Prueger, 2015) was used for most simulations, but we also tested lower densities of 35,000, 45,000, 60,000 and 75,000 plants/ha were also tested because farmers often have poor establishment due to dry spells after planting.

3.6.3 Soil data

The modal soil texture fine grained loamy sand was entered into the Soil Profile File. Saturated hydraulic conductivity (Ksat), volumetric water content at saturation (θsat), field capacity (θFC), and permanent wilting point (θPWP) were estimated using the default values associated with each texture class within the model (Gupta et al., 2020). Based on soil analysis, the upper 0.15 m of the soil was classified as sandy loam (SL), and the layer from 0.15 to 0.60 m was classified as sandy clay loam (SCL). For the top SL layer, the soil constants were: θPWP = 7%, θFC = 16%, θsat = 40%, and Ksat = 1,200 mm/day. For the deeper SCL layer, the values were: θPWP = 16%, θFC = 26%, θsat = 42%, and Ksat = 500 mm/day. This number reflect the fact that the sandy surface drains very quickly but holds little water for plants, while the heavier subsoil holds more water but is slower to take up rainfall.

3.6.4 Field management

Mulching and weed management were calibrated by modifying the default sorghum crop file based on farmers practices. Soil fertility management, however, could not be calibrated because AquaCrop Version 7.1 (2023) does not have specific options for altering fertility levels for the default sorghum files. The model, therefore, assumes non-limiting fertility by default an assumption that is far from true in Mbire, where soils are nutrient poor and farmers apply no fertilizer.

3.6.5 Conservative (nearly constant) parameters

The water productivity parameter normalized for climate (WP) is considered conservative for a given crop type. For C4 crops like sorghum, the typical range is 30–35 g/m² (Geerts *et al*., 2010). However, the actual value used in simulations must be obtained through calibration against local yield data. The potential yield of a cultivar is the yield that can be achieved under optimum management and conditions, without constraints from climate, disease, soil, or nutrition (Abeysiriwardena, 2016). In Mbire, the potential yield is relatively low only 5 to 6 t/ha (Gatti *et al*., 2023) compared to the default sorghum file's yield potential of 9.2t/ha. To cater for the relatively low yield potential an adjusted WP of 30.7 g/m^2 was used. Other conservative input parameters for sorghum were obtained from the default sorghum crop file.

3.6 Evaluation of AquaCrop Performance

In the absence of field experiments, the ability of AquaCrop to simulate potential sorghum yield was assessed by comparing the mean simulated yield from the eight wet and La Niña seasons with potential yield reported in literature (6 t/ha) under perfect field management. As season specific observed potential yield data were unavailable, conventional validation statistics such as Coefficient of Determination (R^2) and Root Mean Square Error (RMSE) could not be calculated. Instead, agreement between simulated and reported yields was evaluated using percentage deviation and a one-sample t-test. Model performance was considered satisfactory when the mean simulated yield did not differ significantly from the literature-derived potential yield ($p > 0.05$), the percentage deviation was small, and the literature value fell within the 95% confidence interval of the simulated yields. Percent deviation was calculated as:

$$\text{Deviation (\%)} = ((\text{Mean } Y_{simulated} - \text{Mean } Y_{literature}) / \text{Mean } Y_{literature}) \times 100 \quad \text{[Equation 1]}$$

Where: $Y_{simulated}$ represents simulated yield, and $Y_{literature}$ represents literature-derived yield.

The ARDAS criterion mean planting day closely matched the modal planting period reported by farmers (second week of November). Accordingly simulated sorghum yield based on the ARDAS criterion were used to evaluate model performance against documented potential yields.

3.7 Definitions and Background Information

Potential yield is the yield of a cultivar that can be obtained under optimum management and conditions in the absence of climate, disease, soil or nutritional constraints. Seasons were classified based on total rainfall: drought (dry or El Niño), total rainfall less than the 44 year mean minus standard deviation (SD) (Nyakudya & Stroosnijder, 2011), wet, total rainfall greater than the 44 year plus SD; and very wet or La Niña total rainfall with ≤ 10% probability of exceedance; and normal total rainfall within one SD of the mean.

3.7. 1 Data Analysis

Soil, crop and climate data were analyzed using descriptive statistics. Total seasonal rainfall and simulated maize yield data was tested for normality using Shapiro-Wilk's test. Seasonal rainfall was found to be normally distributed ($P > 0.05$) whilst simulated crop yields data was not normally distributed ($P < 0.05$). The assumption of normality was violated even after data transformation using the natural logarithm function; therefore, the non-parametric tests were used. Spearman's correlation analysis was used to determine the relationship between total seasonal rainfall and simulated crop yield. The strength of the correlation was interpreted according to (Schober *et al*., 2018) , where coefficients of 0.00–0.19 indicate a very weak relationship, 0.20–0.39 a weak relationship, 0.40–0.59 a moderate relationship, 0.60–0.79 a strong relationship, and 0.80–1.00 a very strong relationship (Papageorgiou, 2022).

The Wilcoxon Signed-Rank Test was used to compare actual and simulated crop yields for the seasons 1990/91 to 2024/24. Friedman test was used to compare sorghum yields among planting dates, planting densities and for maximum ERD. Post hoc test were done using Wilcoxon Signed-Rank tests with a Bonferroni correction depending on the number of pairwise comparisons: for planting time (First versus Second; First versus Third; and Second versus Third) the correction was $\alpha = 0.05/3 = 0.0167$; for plant density (plants/ha) (35,000 versus 45,000; 35,000 versus 60,000; 35,000 versus 75,000; 35,000 versus 90,000; 45,000 versus 60,000; 45,000 versus 75,000; 45,000 versus 90,000; 60,000 versus 75,000; 60,000 versus 90,000; 75,000 versus 90,000) the correction was $\alpha = 0.05/10 = 0.005$; and for maximum ERD

(m) (0.30 versus 0.45; 0.30 versus 0.60; and 0.45 versus 0.60) the correction was $\alpha = 0.05/3 = 0.0167$. All analyses were done using IBM SPSS Version 20.0.

CHAPTER 4: RESULTS

4.1Soil and Crop Data

Soil texture (0.00–0.15 m) occurred at the following frequencies: clay (1), fSCL (3), mSL (2), fSL (5), fLS (4), and fS (1). Mean (SD) soil pH was near neutral, 6.69 (0.36).

Sorghum production among respondents began between 1985 and 2016, with 50% starting after 1999. Most respondents (83.3%) did not have access to a raingauge and did not apply any fertilizer. Most sorghum plantings occurred between the second week and forth week of November (63.3%) with the former being the mode (40.0%). Most farmers (63.3%) achieved 50% crop emergence and rest recorded 50–75% emergence. Farmer practices were distributed as follows: 93.3% no mulch, 53.3% conventional tillage and 33.3 planting basins. Almost all respondents (96.7%) cited 60 days as the time from sowing to flowering.

4.2 Seasonal Rainfall and Reference Evapotranspiration (ETo)

Mean seasonal rainfall (mm) for 1981/82–2024/25 was 691.4 (164.9). There were eight wet (rainfall > 856.3 mm) and La Niña seasons (rainfall > 930.1 mm): 1996/97 (1062.0), 1981/82 (991.1), 2000/01 (970.6), 1998/99 (933.9), 2007/08 (926.3), 1984/85 (916.0), 1988/89 (901.7), and 1985/86 (862.6). Only one wet season occurred in the second period (2003/04–2024/25) and all La Niña seasons were in the first period (1981/82–2002/03), suggesting a declining frequency of wet seasons (Figure 1).

There were seven El Niño seasons (rainfall < 526.4 mm): four in the first period and three in the second period: 1982/83, 2024/25, 2018/19, 1994/95, 1997/98, 2019/20 and 1991/92. The coefficient of variation (CV) of rainfall was moderate but higher in the first (27%) than the second period (19%). Similarly, ETo was similar for the consecutive periods ($p > 0.05$), with low CVs, 9% and 5%, for the first and second periods, respectively (Figure 1).

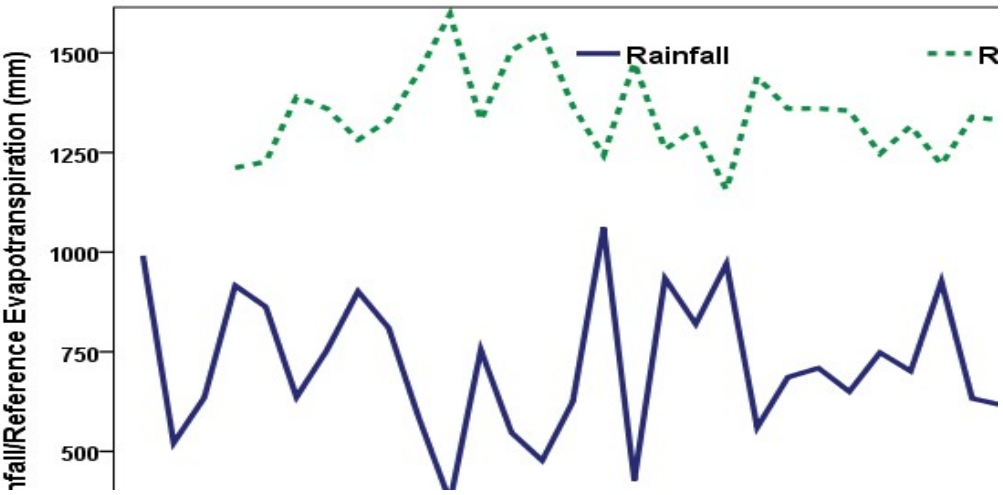

Figure 1. Total rainfall and reference evapotranspiration trends for 1981/82–2024/25 seasons at Mushumbi Pools in Zimbabwe

Seasonal rainfall (mm) increased in the order: dry 460.75 (54.24) < normal 676.81 (90.71) < wet 945.52 (61.47) ($p < 0.001$). Seasonal ETo (mm) followed the same trend: dry 1471.57 (91.76) > normal 1351.49 (65.28) > wet 1228.23 (39.65) ($p < 0.001$).

4.3 AquaCrop Model Performances

The mean simulated sorghum yield (7.21 ± 1.45 t/ha) was marginally different from the literature-derived potential yield (6 t/ha) ($p = 0.05$). The literature value also fell within the 95% confidence interval of the simulated mean (6.00–8.42 t/ha). The percentage deviation between the simulated and literature-derived potential yield was 20%, indicating acceptable/moderate agreement according to Parashar *et al*. (2024)

4.4 Relationship of Crop Yields and Seasonal Rainfall

Spearman's rank correlation analysis showed a moderate positive relationship between total seasonal rainfall and crop yield ($\rho = 0.590$, $P < 0.001$).

4.5 Comparison between Actual and Simulated Sorghum Yields

Simulated sorghum yield (mean ± SD), 5.18 ± 3.08 t/ha was higher than observed yields (0.65 ± 0.18) t/ha ($P < 0.001$).

4.6 The effect of planting dates on sorghum yield

The median planting dates were 25 November, 13 December and 24 December for the first, second and third planting opportunities respectively. The 75th percentile planting dates were 9 December, 19 December and 29 December for the first, second and third planting opportunities

respectively. The Friedman's tests showed that planting date had a significant effect on sorghum yield (χ^2=30.772, P < 0.001) (Figure 2). Wilcoxon post hoc tests with Bonferroni correction (α = 0.0167) showed that the first and second planting dates produced similar yields (P > 0.0167), which were 1.31 times more than that of the third planting date (P < 0.001).

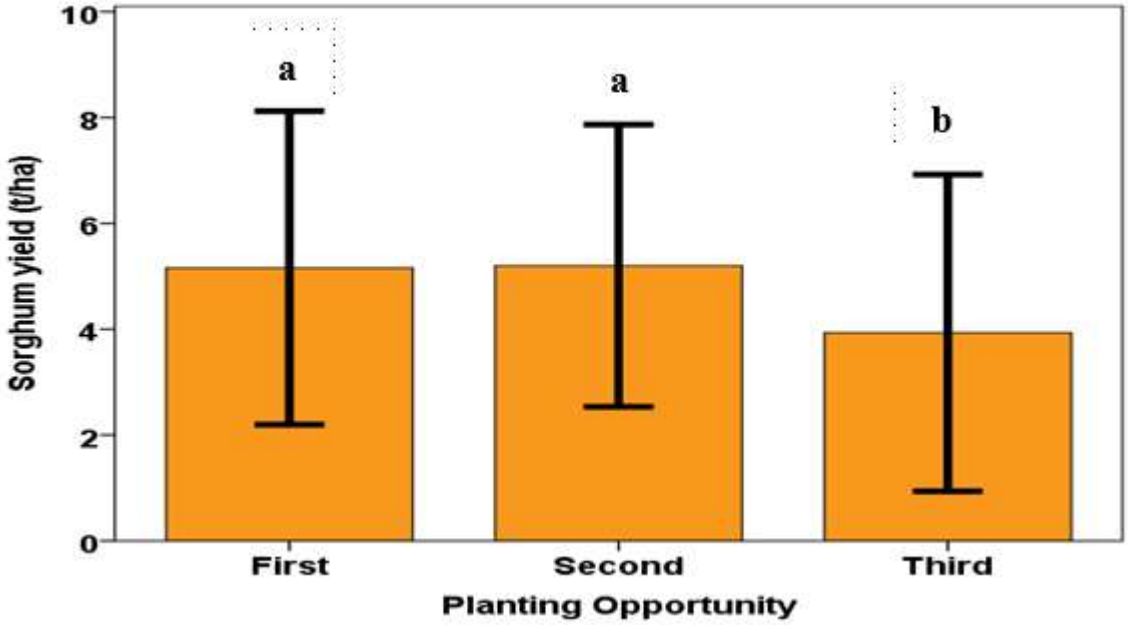

Figure 2. Variation of sorghum yield with planting date (Error bars represent standard deviations)

4.7 The effect of plant density on sorghum yield

Friedman's test showed that plant density had a significant effect on sorghum yield (χ^2=52.885, P < 0.001). Wilcoxon post hoc tests with Bonferroni correction (α = 0.005) showed that sorghum yield generally increased marginally (P < 0.005) with increasing plant density with the highest increase (3.9%) being observed when density increased from 35,000 to 75,000 plants/ha.

Table 1. Effect of plant density on sorghum yield

Plant density (plants/ha)	Yield (t/ha)
35,000	5.02±2.90[a]
45,000	5.07±2.93[bc]
60,000	5.05±2.98[b]

75,000	5.22±3.12[c]
90,000	5.08±3.06[ac]

4.8 The effect of maximum ERD on sorghum yield

Friedman's test showed that there were differences in effect of maximum ERD on sorghum yield (χ^2=52.198, P < 0.001) (Figure 3). Wilcoxon post hoc tests with Bonferroni correction (α = 0.0167) showed that yield increased (p < 0.0167) by 18.2, 35.5 and 14.6% when max ERD (m) increased from 0.30–0.45, 0.30–0.60, and 0.45–0.60, respectively.

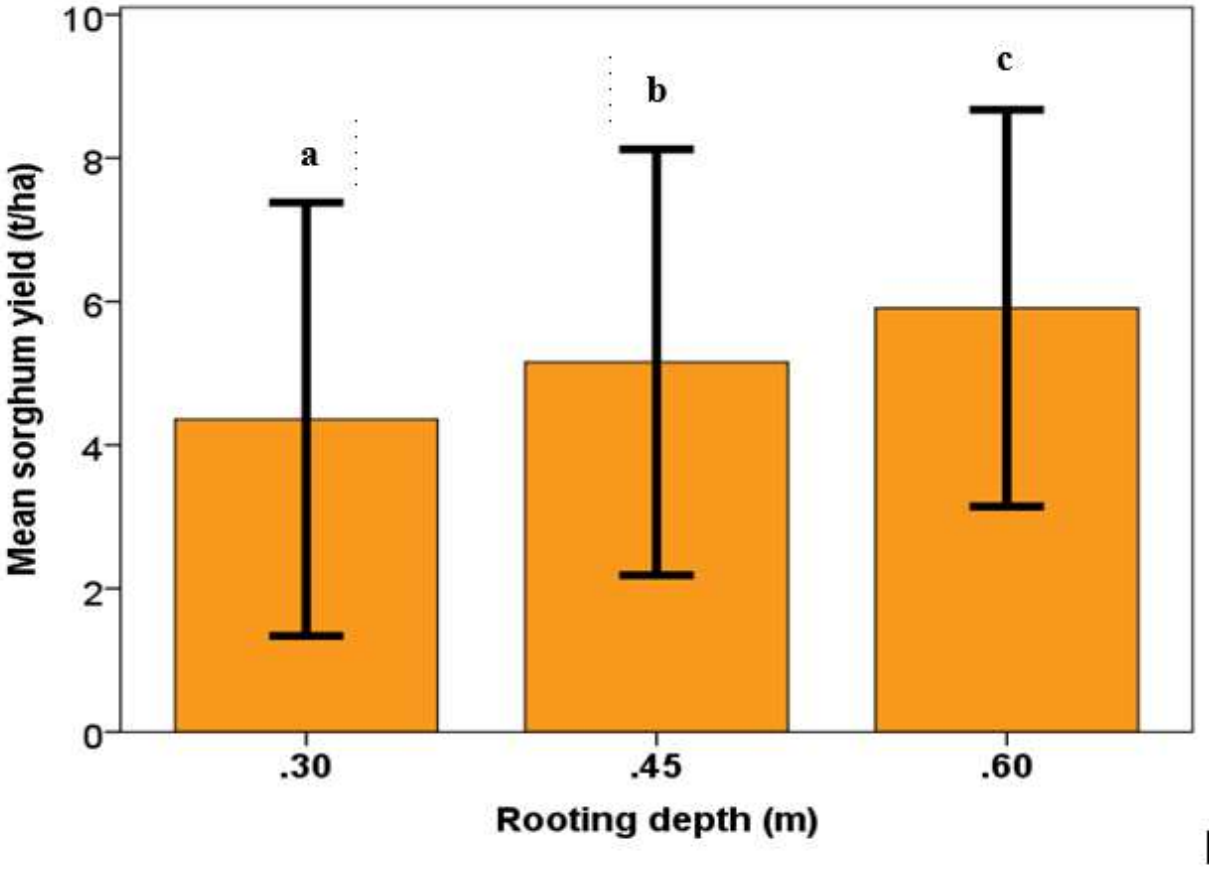

Figure 3. Effect of rooting depth on sorghum grain yield (Error bars represent standard deviations)

CHAPTER 5: DISCUSSION

5.1 Soil type, Seasonal Rainfall and Reference Evapotranspiration

Soils in the area range from medium to heavy textured, which are ideal for sorghum production, and the pH (6.69) was close to the recommended range (5.0–6.5) (Ministry of Agriculture, Mechanization and Irrigation Development, 2011). Mean rainfall (1981/82–2024/25), 691.40 mm, and that of dry seasons, 460.75 mm are within the range required for sorghum production (300–900 mm); reaffirming that the major problem is rainfall distribution rather than absolute water shortage. Additionally, very high inter-seasonal variability in dry and normal years makes the area marginal. Wet seasons rainfall (945.52 mm) also fall in the optimal range for sorghum production (500–1,000 mm) (Assefa *et al*., 2010). High rainfall may not be problematic because sorghum is tolerant to transient waterlogging.

5.2 Relationship between Sorghum Yield and Seasonal Rainfall

The moderate positive relationship between total seasonal rainfall and sorghum yield ($\rho = 0.590$, $P < 0.001$) indicates the important role played by total seasonal rainfall in determining sorghum productivity within the study area. These findings were expected because rainfall is the primary source of water for crop growth in rainfed farming systems. Adequate rainfall promotes seed germination, nutrient uptake, photosynthesis, and biomass accumulation, all of which contribute to improved crop growth and yield formation. However, the moderate strength of the correlation suggests that seasonal rainfall alone does not fully explain the observed variations in yield. Other factors such as rainfall distribution, soil fertility, temperature, crop management practices, cultivar characteristics, pest and disease incidence, and soil moisture retention capacity may also have influenced crop performance. For example, prolonged dry spells during critical growth stages such as flowering and grain filling can reduce yields even when total seasonal rainfall is adequate. Under such conditions, improving water use efficiency through practices such as conservation agriculture, soil moisture conservation, and the adoption of drought tolerant crop varieties may help reduce the negative impacts of rainfall variability and enhance crop productivity under changing climatic conditions.

5.3 Comparison between Observed and Simulated Sorghum Yields

The large difference between mean simulated sorghum yield (5.18 t/ha) and observed yield (0.65 t/ha) indicates the presence of a substantial yield gap (87.5%) between actual and potential yields. The large yield gap may be attributed to sub optimal management of production factors such as soil fertility, water, and pests and diseases; and poor agronomic practices (Muroyiwa et

al., 2022; Yali & Begna, 2022). The large yield gap highlights opportunities for improving productivity through enhanced soil fertility management, improved agronomic practices, and efficient water management strategies.

5.4 Effect of Planting Date on Sorghum Yield

Respondents reported that most sorghum plantings occurred between the second week and forth week of November (63.3%) with the former being the mode (40.0%). Therefore, farmers' plantings closely approximated mean planting date under the first planting opportunity (25 November). Planting date significantly influenced sorghum yield, demonstrating the importance of timely planting in maximizing sorghum productivity. The similar yields obtained from the first and second planting opportunities suggest that both planting windows provided favorable environmental conditions for crop growth and development. In contrast, the lower yields associated with the third planting opportunity indicate that delayed planting reduced the crop's ability to fully utilize available rainfall and growing season resources. Late plantings often coincide with end of season dry spells that affect the late reproductive and grain filling stages.

Relatively low yields under late planting may be attributed to shortened growing periods, increased exposure to terminal drought, and moisture stress during critical reproductive stages. Late planted crops often experience declining soil moisture availability during flowering and grain filling, resulting in reduced biomass accumulation and grain production.

These findings are consistent with previous studies that reported significant yield reductions associated with delayed planting in sorghum producing regions. Research conducted in SSA shows that early planting enables crops to exploit seasonal rainfall more effectively and avoid water stress during reproductive development, leading to higher yields (Owusu Danquah *et al*., 2025). Similar studies using AquaCrop demonstrated that delayed planting reduces yield by exposing crops to less favorable moisture and temperature conditions later in the season (Abdalhi & Jia, 2018).

The findings highlight the importance of timely planting as an adaptation strategy for improving sorghum productivity under variable climatic conditions. Results from this study suggest that despite not having access to rain gauges most farmers' planting fell within the first planting window based on the ARDAS criterion hence the large yield gap was not largely due to late planting.

5.5 Effect of Plant Density on Sorghum Yield

Plant density significantly influenced sorghum yield, indicating that plant population is an important determinant of productivity. Yield generally increased with increasing plant density, reaching a maximum at 75,000 plants/ha, although the magnitude of the increase was relatively small. This suggests that sorghum was able to maintain stable yields across a wide range of plant populations, reflecting its capacity to compensate for differences in stand density through adjustments in plant growth and yield components.

Higher yields observed at intermediate to high plant densities may be attributed to improved utilization of available resources, including light, water, and nutrients. At lower plant densities, the available growing space may not have been fully exploited, resulting in reduced overall productivity per unit area. However, the slight decline in yield at 90,000 plants/ha suggests that excessive plant populations may have increased competition among plants for limited resources, thereby reducing the benefits associated with higher densities.

These findings agree with previous studies that reported increased sorghum yields with increasing plant density up to an optimum level, beyond which yield gains either plateau or decline due to increased intra-specific competition (Shahrajabian *et al*., 2020). Research conducted in semi-arid environments has shown that optimum sorghum populations typically range between 60,000 and 80,000 plants/ha, depending on cultivar characteristics, rainfall availability, and soil fertility conditions(Nassary *et al*., 2025). Similar results have also been reported in AquaCrop simulation studies, where moderate increases in plant density improved canopy development and resource capture, resulting in higher yields (Fallah *et al*., 2025).

The results suggest that plant populations around 75,000 plants ha^{-1} may provide favorable conditions for maximizing sorghum productivity under the environmental conditions represented in this study. This plant density exceeds 30,000 observed in farmers' fields and 60,000 plants/ha recommended by Seed Co but it is lower than the ceiling of 90,000 plants/ha recommended by the Ministry of Agriculture, Mechanization and Irrigation Development (2011).

5.6 Effect of Maximum ERD on Sorghum Yield

Sorghum yield increased as maximum ERD increased from 0.30 m through to 0.60 m. This response was expected because deeper root systems enable crops to exploit a larger soil volume for water and nutrient uptake, thereby enhancing resilience to periods of water deficit and improving overall crop performance. In contrast, shallow rooting depths restrict access to water

stored in deeper soil layers, increasing the susceptibility of crops to moisture stress during critical growth stages. The substantial yield increases observed with increasing rooting depth indicate that root development is an important factor determining sorghum productivity under rainfed conditions.

The findings align with existing literature suggesting that deeper rooting systems improve crop water extraction and increase yield, particularly in semi-arid environments (Prakash *et al*., 2022). Studies using AquaCrop have similarly demonstrated that increasing rooting depth enhances water uptake, biomass production, and grain yield by allowing crops to access additional soil water reserves (Manschadi et al., 2006). Results of this study highlight the importance of soil and crop management practices that promote root development and improve access to deeper soil moisture. Such practices may contribute to enhanced water use efficiency and greater yield stability under variable climatic conditions.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6. 1 Conclusion

This study evaluated the effects of seasonal rainfall, planting date, plant density, and maximum ERD on sorghum yield in Mbire District using the AquaCrop model. The results showed that seasonal rainfall had a significant moderate positive influence on sorghum productivity, confirming the importance of water availability in determining crop performance under rainfed conditions. However, the moderate strength of the relationship between rainfall and yield suggests that rainfall alone does not account for all yield variability and that factors such as soil fertility, crop management practices, and soil moisture conservation also play important roles. The study further revealed a substantial yield gap (87.5%) between simulated and actual sorghum yields, indicating that farmers are currently producing well below the yield potential of the crop.

The study also demonstrated that agronomic management practices significantly influence sorghum productivity. Planting during the first or second planting opportunity resulted in higher yields than planting at the third opportunity, highlighting the importance of timely crop establishment for effective utilization of seasonal rainfall. In addition, deeper rooting depths significantly enhanced yield by improving access to soil moisture stored in deeper soil layers. Overall, the findings indicate that substantial opportunities exist to improve sorghum production in Mbire District through improved agronomic management, enhanced soil moisture utilization, and practices that promote deeper root development. The study also demonstrated the usefulness of the AquaCrop model as a decision support tool for evaluating management options and identifying strategies for increasing sorghum productivity under semi-arid conditions.

6.2 Recommendations

6.2.1 Recommendations for Practice

Based on the findings of this study, in order to improve sorghum yield the following recommendations were derived:

- Planting at the first or second planting opportunity based on the ARDAS criterion;
- Planting at densities between 45,000 and 75,000 plants/ha; and
- Increasing maximum ERD from the observed 0.30 m to 0.45 m or 0.60 though breaking root growth limiting layers or deeper rooting cultivars.

6.2.2 Recommendations for Research

The following further research is recommended:

- Conducting field experience to test the recommendations state in section 6.2.1 above; and
- Performing robust climate data analysis in order to determine the effect of other climate variables (dry spells, heat waves and ETo) on sorghum yield in the area.

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