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CASE STUDY

The effect of irrigation practice and water consumption using aqua-crop

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ABSTRACT

BACKGROUND AND OBJECTIVES: The study explored the relationship between irrigation practices, water availability, and soil fertility in relation to crop yield. The investigation analyzed three distinct irrigation scenarios, namely full irrigation, deficit irrigation, and rain fed agriculture. The primary objective of the study was to evaluate the correlation between irrigation practices and soil fertility. To achieve this, the study incorporated different soil fertility levels, with high levels representing unlimited fertility for both full and deficit irrigation, and low levels corresponding to rain fed conditions. This design is primarily used to isolate the effects of irrigation practices on crop yields under a variety of fertility scenarios. The study also looks into how to achieve sustainable water management in the agricultural sector.
METHODS: Aqua-crop, a computerized model, was utilized mimic real-life crop harvests. The aqua crop model was used to simulate crop yield in response to water availability. The calibration of the model involved utilizing data on various crop growth parameters, including soil fertility, crop canopy cover, evapotranspiration, soil water movement, crop yield and harvest index percentage. This innovative study utilizes aqua-crop to analyze the impact of irrigation methods on crop yields under controlled settings, effectively isolating irrigation influences from soil discrepancies. This approach is well-suited for studying sustainable water management strategies in agriculture, a pressing concern in light of worldwide water water scarcity.
FINDINGS: Aqua-crop simulations revealed that consistent irrigation with a full irrigation system and high efficiency (70 percent) resulted in high yields. The simulated yields (8.48 to 10.04 tons per hectare) were significantly higher than farmers' actual yields (3.86 to 4.74 tons per hectare). Discrepancies between farmer irrigation methods and the model's assumption of uniform water application are the probable cause of the variation, underscoring the significance of considering real-world intricacies in the interpretation of model outcomes. The observed yield differences despite similar irrigation systems indicate the potential impact of unaccounted for factors such as soil type variations and real-world farmer practices (e.g., fertilization). Nevertheless, a substantial R-squared value of 0.85 suggests a robust association between simulated and observed yields, suggesting that aqua-crop can be valuable in comprehending overall irrigation-yield connections. Emphasis is placed on considering real-world complexities to achieve optimal crop yield. Aqua-crop simulations analyzed the correlation between irrigation and water use efficiency. Although full irrigation resulted in the highest simulated yields, deficit irrigation enhanced evapotranspiration water productivity. This seemingly contradictory finding can be explained by diminishing returns: deficit irrigation may result in slightly lower yields but higher water efficiency, highlighting the importance of considering both yield and water use efficiency when making long-term irrigation decisions. has highlighted the disparity between projected and actual crop yields, underscoring the significance of incorporating practical factors into the simulation of irrigation techniques. This finding holds particular relevance in areas where water resources are limited.
CONCLUSION: The Food Agriculture Organization's aqua-crop is a useful tool for farmers who have limited access to water. Aqua-crop is a computer-based model that replicates the growth of crops in different irrigation scenarios. It provides farmers with the opportunity to explore the correlation between water usage and crop yield. By doing so, they can determine the most effective irrigation strategies that optimize harvest while minimizing water consumption. This aspect holds particular significance in regions facing water scarcity.

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53	7	0

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INTRODUCTION

The ever-increasing demand for water threatens sustainable development (Hertel, 2011; Ahmadi *et al.*, 2020). The management and utilization of water resources are subject to the influence of several factors. These factors encompass population growth, economic development, land-use practices, climate change, and societal customs and beliefs. The interplay between these elements shapes the strategies and approaches employed to ensure the efficient and sustainable use of water resources (Ghorbani *et al.,* 2021; Mwangu, 2021). The growing emphasis on water resource development, such as dam building for agriculture and hydropower, has unintended consequences. These projects alter land cover, which could harm the environment and biodiversity (Reid *et al.,* 2019). Economic expansion, although propelling progress, often leads to environmental deterioration, as the pursuit of this growth entails heightened water usage, modified river patterns, and ecological damage (Pande *et al.,* 2020; Teweldebrihan *et al.,* 2023). Agricultural development, often driven by economic growth, can be especially harmful because it may prioritize short-term gains over long-term environmental health (den Besten *et al.,* 2016; Vysochyna *et al.,* 2020). Human health is inextricably linked to agricultural water systems (Schwarzenbach *et al.,* 2010; Lin *et al.,* 2022). Several potential strategies for wastewater treatment have been identified through extensive studies and reviews. These approaches aim to maximize the efficiency of pollutant removal while simultaneously ensuring cost-effectiveness (Kumar *et al.,* 2024). Finding a sustainable path forward necessitates thoroughly understanding this interdependence (Kandasamy *et al.,* 2014; Lyu *et al.,* 2020). A key challenge is managing various users' competing demands on water resources (Haddeland *et al.,* 2014). This competition frequently disadvantages those with less economic clout or whose needs are difficult to quantify, such as downstream communities, smallholder farmers, and the environment (De Graaf *et al.,* 2014; Kaufmann *et al.,* 2021; Schultner *et al.,* 2021). The development of sustainable water management strategies requires a delicate balance between conflicting demands, while also guaranteeing that all stakeholders, including the environment, have access to the necessary water resources (Falk *et al.,* 2018; Vink, 2018). Ensuring the long-term health of the water resources and the environment as a whole necessitates the efficient treatment and environmentally responsible production for long-term sustainability (Kamyab *et al.,* 2023). Farmers have relied on experience and intuition to manage water resources (Knox *et al.,* 2012; Corral *et al.,* 2017). The advent of recent technological advancements has ushered in a potent and innovative methodology: optimization through modeling driven by information (Ketema *et al.,* 2020; Hidayati, 2021). This provides a much more precise understanding of environmental conditions than ever (Brauman *et al.,* 2013; Degife *et al.,* 2021). In agro-industrial farming, for example, these models can calculate the water crops required at any given time, allowing for efficient irrigation schedules (Ramachandran *et al.,* 2022). This saves water and boosts crop yields (Montoya *et al.,* 2016). The agricultural industry in Ethiopia serves as the primary economic driver for the country, playing a crucial role in the Gross domestic product (GDP) and export earnings, as well as being the main source of employment for the majority of the population (Hagos *et al.,* 2009; Chamberlin *et al.,* 2012). Ethiopia's reliance on rain-fed agriculture makes it extremely vulnerable to weather and climate change (Asfaw *et al.,* 2019). Catastrophic crop failures can occur due to rainfall deficiencies, droughts, or even short periods of dry weather throughout the growing season (Adimassu *et al.,* 2014; Araya *et al.,* 2015; Jemberie *et al.,* 2016). This domino effect leads to food shortages, food insecurity, and a decline in agricultural income generation (Teweldebrihan *et al.,* 2021). The challenge is further intensified by the erratic nature of weather patterns (Dawit *et al.,* 2019). Consider Ethiopia, which has four distinct seasons: winter (Kremet), summer (Bega), spring (Belg) and lent (Tseday), each with significant differences in precipitation levels and intensity (Dinka *et al.,* 2019; Angualie et al., 2021). These variations greatly impact future water runoff (Dawit *et al.,* 2020). In arid and semi-arid regions, the issue is further aggravated as evaporation rates consistently surpass the amount of rainfall received annually (Xu *et al.,* 2001; Tang *et al.,* 2016). Precipitation is also unevenly distributed, resulting in frequent droughts that stress crops (Abedinpour *et al.,* 2012). The Intertropical Convergence Zone (ITCZ's) unpredictable nature exacerbates the problem (He *et al.,* 2022). The ITCZ's movements vary because it is sensitive to variations in Indian Ocean sea surface temperatures.

These challenges highlight Ethiopia's critical need for water security (Ye *et al.,* 2013; Gong *et al.,* 2020). The scholars indicated that, achieving this goal requires significant investment in water infrastructure and management capacity (Foster *et al.,* 2020; Gaaloul *et al.,* 2021). This phenomenon has a direct impact on the timing and duration of rainy seasons, causing frequent droughts and making water availability unreliable. The intensity of many storms exceeds the soil's infiltration rate, causing excessive runoff. By diverting precious water resources, this runoff negatively impacts crop growth and exacerbates soil erosion, resulting in the deterioration of land quality and ecological resources. The combination of unpredictable rainfall and runoff complicates sustainable water management in agriculture. It is imperative to implement sustainable water management techniques and conduct studies on drought-resistant crops and irrigation technologies in order to reduce the impacts of erratic rainfall patterns and secure the future sustainability of Ethiopia's agricultural industry. This is where technology, particularly data-driven modelling, becomes an important tool for optimizing water use, mitigating runoff, and ensuring long-term agricultural viability (Kamyab *et al.,* 2023). This study tackles a crucial obstacle by guaranteeing the implementation of sustainable water management practices in agriculture, specifically in areas such as Ethiopia that heavily depend on erratic rainfall patterns. The innovation is in the use of data-driven modeling, which is a significant improvement over traditional experience-based methods. The approach provides

a significantly enhanced comprehension of environmental factors, enabling the implementation of irrigation timetables that are more effective in conserving water and boosting agricultural productivity. This is critical for Ethiopia's agriculture sector, the country's economic backbone, which is highly vulnerable to climate change and unpredictable weather. The work seeks to reduce risks and ensure Ethiopian agriculture's long-term viability by implementing sustainable water management strategies and researching drought-resistant crops and irrigation technologies. The primary objectives of the present study involve examining strategies for attaining sustainable water management within the agricultural industry. The increasing need for water poses a threat to sustainable growth, especially in rain-fed agriculture. Innovative approaches, like data-driven modeling, are commonly seen as efficient means to optimize water utilization and guarantee the enduring viability of agricultural practices. The study was conducted in Ethiopia in 2024 and recognizes that traditional experience-based methods are no longer adequate.

MATERIALS AND METHODS

The study was conducted in the Amhara region of Ethiopia, and the study focuses on Debre Birhan. The Amhara region is notable for being one of Ethiopia's largest and most productive agricultural areas (Fig. 1). The study area is located between $38^0\,73' - 40^o\,00'$ Latitude and $9^o00' - 10^o30'$ Longitude. Debre Birhan is noteworthy for its extensive irrigation systems, which have been implemented at communal and individual farmer levels. Due to its extensive utilization, the area serves as an optimal site for investigating the influence of irrigation techniques on crop productivity, water utilization effectiveness, and the overall sustainability of agricultural practices (Fig. 2). Through the examination of data in this particular area, scholars have the opportunity to acquire significant knowledge that can be utilized in addressing water scarcity challenges and enhancing agricultural productivity in various regions by implementing efficient irrigation techniques.

Aqua-crop model

The aqua-crop model, created by the Food and Agriculture Organization (FAO), serves as a valuable resource for examining and overseeing crop yields in light of water availability. This model is commonly employed for the design and management of irrigation systems. The model's effectiveness stems from its ability to simulate crop yield under various environmental conditions. By adjusting input parameters, individuals can predict how crops will react to changes in water availability, temperature, and weather patterns. The simulated data facilitates well-informed decision-making regarding irrigation strategies and the allocation of resources. Aqua-crop's versatility extends to a wide range of major herbaceous crops, including fruits, grains, root vegetables, leafy greens, and even forages harvested multiple times during the season. The model tracks important growth stages for each variety of crop, providing a deeper insight into their growth

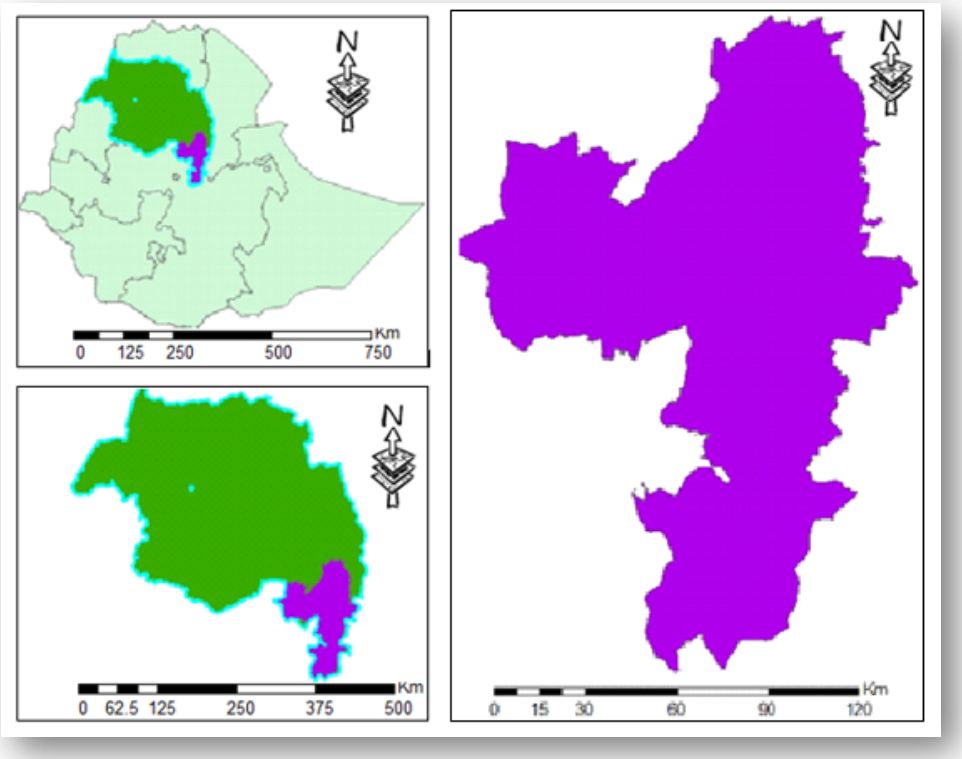


Fig. 1: Geographic location of the study area in the Amhara region of Ethiopia

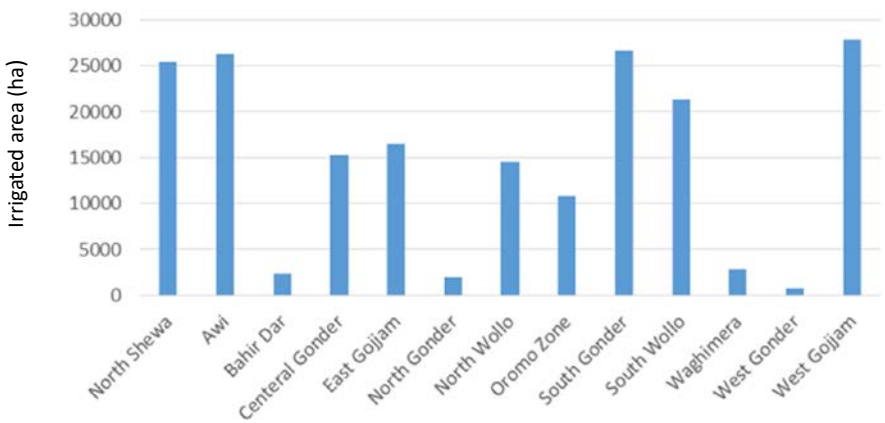


Fig. 2: The actual irrigated area

patterns. For instance, it takes into account crucial phases like germination, onset of flowering, peak root development, and ripening in the majority of crops. In the case of forage crops, the focus might be on germination or regrowth, harvest timings, and senescence. This tailored approach ensures that aqua-crop delivers relevant and valuable insights for optimizing irrigation practices and increasing crop yields. The main objective of this study is to simulate aqua-crop in order to analyze the water needs of crops and their corresponding yield production. The aqua-crop model simulates crop yield and water use

under a variety of conditions in which Eq. 1 is used to quantify the impact of water scarcity on yield. To address the relationship between crop yield and water use, the proposed Eq. 1 was relative yield reduction versus the corresponding relative reduction in evapotranspiration (ET). Eq. 1 expresses the yield response to ET (FAO, 2012):

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right) \quad (1)$$

Where;

Yx and Ya are the maximum and actual yields

ETx and ETa are the maximum and actual evapotranspiration

Ky is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses.

The yield response factor (Ky) captures the essence of a crop's complex linkages between production and water use, which involve numerous biological, physical, and chemical processes. The relationship has demonstrated remarkable validity, allowing for a workable procedure for quantifying the effects of water deficits on yield. The approaches utilized to assess the productivity response to water scarcities through Eq. 1 are concisely explained in the subsequent paragraphs.

Calculation procedures

The procedure for calculating the actual yield using Equation 1 Ya follows four steps:

a) Determine an adapted crop variety's maximum yield (Yx) based on its genetic makeup and climate, assuming that agronomic factors such as water, fertilizers, pests, and diseases are not limiting.

b) Calculate maximum evapotranspiration (ETx) using established methodologies, assuming crop water requirements are fully met.

c) Determine the actual crop evapotranspiration (ETa) under the given conditions, as determined by the crop's available water supply.

d) Determine actual yield (Ya) by properly selecting the response factor (Ky) for the growing season or across the various growing stages.

The aqua-crop model simulates crop yield over four consecutive daily steps. First, it monitors green canopy cover (CC) growth, which is influenced by soil water content. Crop transpiration (Tr) is calculated under well-watered conditions using reference evapotranspiration and the CC. Water stress can impact both CC and Tr. The aboveground biomass (B) can be determined by utilizing the total transpiration (Tr) and a biomass water productivity (WP) value that has been modified to account for varying climatic factors. Finally, crop yield (Y) is calculated from B using a harvest index (HI) that accounts for stress effects.

Model input data

The aqua-crop model's input includes daily climatic data (such as sunshine hours, daily minimum and maximum temperatures, and daily rainfall), crop phenology information pertaining to various canopy attributes, rooting depth, as well as the crop's reactions to water, salinity, and fertility stress. The research study collected the necessary climatic data for the Aqua-crop model, including sunshine hours, daily minimum and maximum temperatures, and daily rainfall. The potential evaporation was calculated in the study using the Penman-Monteith method, as demonstrated in Eq. 2 (Chen *et al.*, 2005):

$$ET_O=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)} \quad [2]$$

Where;

ETo = Reference evapotranspiration in mm per day

Rn = Net radiation at the crop surface

G = Soil heat flux density

T = Mean daily air temperature at 2 m height

U2 = Wind speed at 2 m height

e_s = Saturation vapour pressure

e_a = Actaul vapour pressure

Δ = Slope vapour pressure curve

γ = Psychrometric constant

The yield response to water

The perception of how water affects crop yields is consistently evolving. Historically, it was conventionally believed that there existed a direct correlation between the amount of water utilized and the productivity of crops. Intercepted solar radiation is the primary driver of transpiration (the release of water vapor from plants) and photosynthesis. Consequently, a direct relationship was observed: higher water consumption through transpiration led to greater biomass generation, ultimately resulting in higher crop yields. This linear relationship does not adequately capture the complexities of plant growth. The FAO Irrigation and drainage paper No.

33, published in 1979 by Doorenbos and Kassam (1979), reflected this earlier understanding. A yield response was suggested for the water approach, which postulated that there would be a proportional decrease in yield with every reduction in evapotranspiration, encompassing both soil evaporation and plant transpiration. This approach provided a solid foundation but failed to account for factors such as plant resilience, water use efficiency, and water stress's impact on different growth stages. With the progression of research, there is a deepening comprehension of the water needs of crops, leading to the development of advanced models and irrigation techniques aimed at optimizing crop yield and preserving water resources.

The management

Aqua-crop provides a comprehensive suite of crop management tools. These tools are divided into two categories: irrigation management and field management. Irrigation management exhibits greater resilience compared to the other option, showcasing a variety of characteristics. Users have the ability to establish different irrigation tactics, such as scheduling, volume, and application methods, which grants them meticulous authority over the distribution of water. This feature helps optimize water usage and ensure crops get the exact amount of moisture they require to thrive. While, aqua-crop's field management capabilities are limited compared to irrigation management, they still provide useful functionality. The model provides users with the ability to analyze a range of field practices that influence crop growth, such as seeding schedules, plant density, and fertilizer application. While not as detailed as some dedicated field management models, aqua-crop's features provide a foundation for understanding how these practices interact with water availability to affect crop performance. Aqua-crop's integrated approach to irrigation and field management renders it a proficient instrument for making well-informed choices and enhancing agricultural output.

Estimating water use and irrigation application with aqua-crops

Traditionally, estimating irrigation requirements has been an imprecise process based on experience. The aqua-crop model offers an advanced approach to calculating water usage and enhancing irrigation practices. Aqua-crop considers a variety of factors that influence crop water requirements. These include climatic data (temperature, humidity, and radiation), soil properties (water-holding capacity and drainage), and crop-specific characteristics. The model possesses the ability to assess the overall water demands of a crop during the entire growing season, taking into consideration these specific factors. Users are empowered by the model to simulate a wide range of irrigation scenarios. They have the flexibility to define irrigation methods, including sprinkler or drip systems, and schedule irrigation events by specifying the timing, depth, and water quality. Furthermore, the model offers the convenience of automatic irrigation scheduling based on pre-defined parameters, such as fixed intervals or the maintenance of a specific soil moisture level. Aqua-crop's functionalities enable farmers to evaluate the impact of various irrigation strategies on crop growth and water efficiency. This allows farmers to make data-driven decisions, using the exact amount of water required to maximize yields while minimizing water waste. The precise method of applying irrigation is of utmost importance for the sustainable water management in agriculture, particularly in areas where water resources are limited.

Irrigation management

The irrigation management tools are effective. This package enables users to evaluate and analyze crop yield and water use efficiency in rain-fed and irrigated systems. Choosing between irrigation methods such as sprinkler, surface, or drip (including both surface and subsurface drip systems) is a significant advantage. This enables the customization of irrigation strategies based on the unique needs of different crops and soil conditions. Additionally, users have the capability to develop comprehensive irrigation schedules by specifying the precise timing, depth of water application, and even the irrigation water quality used for each event. Aqua-crop's versatility includes automatic schedule generation based on user-defined parameters such as fixed time intervals, specific application depths, or a predetermined soil moisture depletion level. This level of automation can be a significant time saver for farmers managing large fields. The model also possesses the capability to calculate the total water demand of a crop given

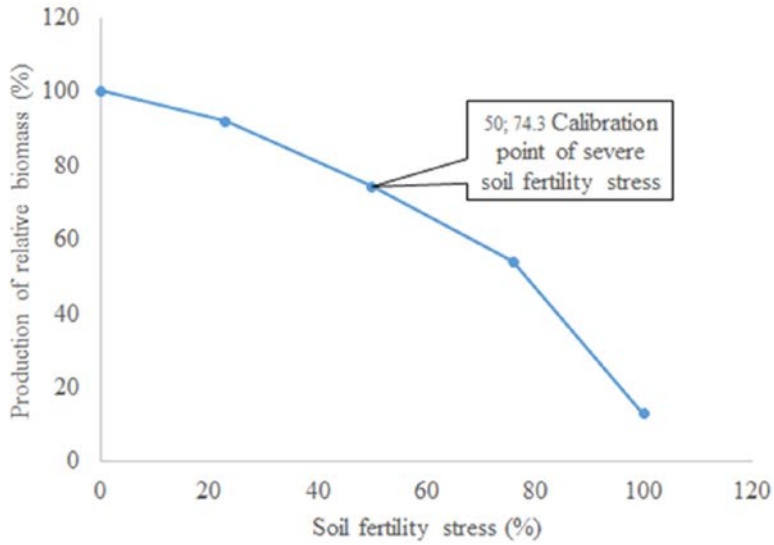


Fig. 3: The calibration of soil fertility stress and crop response

particular weather conditions, which serves as an added advantage. This information is critical for developing a baseline irrigation strategy and optimizing water usage throughout the growing season. Aqua-crop's extensive irrigation management capabilities empower farmers to make well-informed choices that optimize crop production and minimize water wastage. Aqua Crop uses climatic data (temperature, humidity, and radiation), soil properties, and crop characteristics to estimate a crop's total water requirements for the growing season.

Aqua-crop model calibration and validation

The aqua-crop model was calibrated using data on crop growth parameters such as soil fertility, crop canopy cover, evapotranspiration, water movement in the soil, crop yield and percentage of harvest index. Hence, all the parameters were acquired from primary and secondary data sources (Fig. 3). Aqua Crop simulations incorporated a variety of water application depths and soil fertility levels. The data were utilized to adjust the crop's reaction to soil fertility, which is closely linked to the production of relative biomass and aids in estimating the yield in varying soil soil conditions (Abedinpour *et al.,* 2012; Montoya *et al.,* 2016; Trombetta *et al.,* 2016).

RESULTS AND DISCUSSION

The analysis of crop yield production was conducted across different conditions in order to gain a deeper understanding of the correlation between irrigation practices, water availability, and soil fertility levels. The scenarios analyzed included full irrigation, deficit irrigation (where water is applied less than the full crop requirement), and rainfed agriculture (which relies solely on rainfall). A notable differentiation was established in terms of soil fertility: the complete and insufficient irrigation scenarios presumed boundless soil fertility, while the rainfed scenario presumed moderate soil fertility. This distinction recognizes that soil quality can impact crop yields regardless of water availability which correlates to other studies (Teweldebrihan *et al.,* 2024). The analysis centered on the influence of irrigation, precipitation, water application depth (the quantity of water administered per irrigation occurrence), and soil fertility on the productivity of crops. The FAO'S aqua-crop simulates crop growth and estimates water requirements based on climate, soil properties, and crop characteristics, including irrigation strategies (timing, amount, and method) to optimise water use for potatoes. The model aids in calculating the complete water needs of a potato throughout its growth period. The simulation model considered the growth specifics of the potato crop. Optimal irrigation and fertile soil contribute to achieving the maximum yields of up to 10 tons per hectare. The yield of crops can be influenced by the amount and timing of water applied during irrigation.

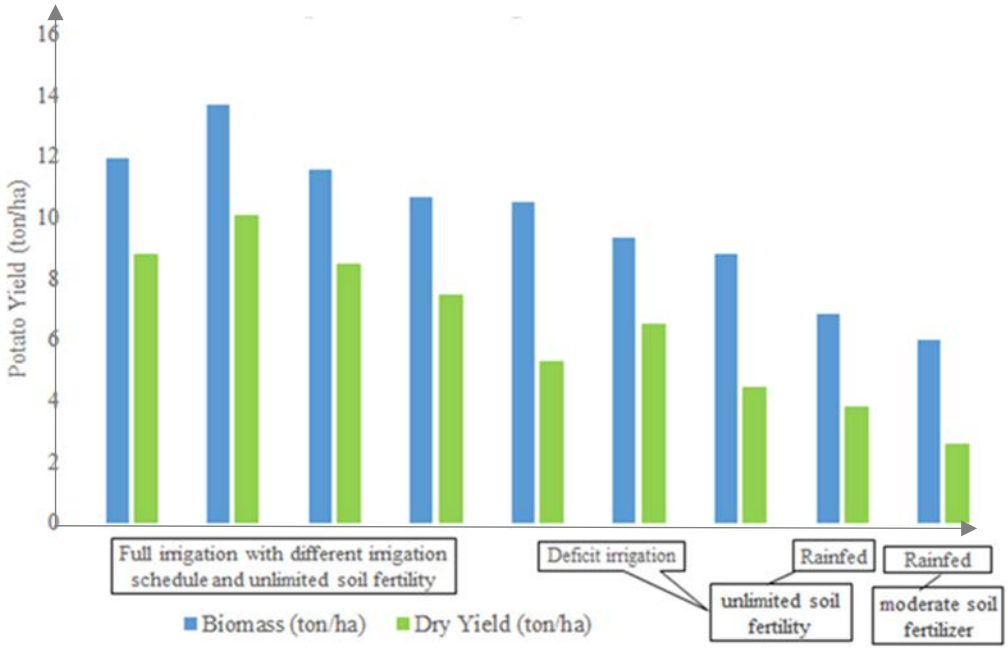


Fig. 4: The yield response to water application and soil fertility

Implementing deficit irrigation techniques can help conserve water resources, albeit resulting in a slight reduction in crop yields. The findings revealed that full irrigation with unlimited soil fertility yielded the highest yields, reaching 13.69 tons per hectare of biomass and 10.05 tons per hectare of dry yield at an application depth of 70 millimetres (Fig. 4). The importance of consistency is underscored by the notable positive effects it brings. The study revealed that crop yields showed fluctuations based on the precise depth of water application and timing of irrigation in both full and deficit irrigation conditions. The results indicate that enhancing irrigation techniques beyond simply supplying adequate water can result in increased crop yields. Having a grasp of these intricacies empowers farmers to make educated choices regarding irrigation methods that enhance crop productivity and potentially improve water usage efficiency.

Comparison between the observed and simulated result

The examination involved a comparison between the crop yields achieved through conventional farming methods and those predicted by the aqua-crop model. Specifically, the study concentrated on potato crops cultivated on small-scale farms that utilized furrow irrigation systems. To account for differences in irrigation practices, the researchers used the aqua-crop model to simulate various scenarios, including full and deficit irrigation strategies. Aqua-crop is a computer-based model that predicts crop yields based on varying water availability conditions. The model estimates actual yield by taking into account reductions in evapotranspiration (ET) due to water scarcity. A yield response factor describes the complex effects of water scarcity on crop yield.

Difference between modeled and observed crop yields

This section investigates the discrepancy between the crop yields predicted by the aqua-crop model and the actual yields measured on smallholder plots. Crop yields were subsequently assessed on the individual plots owned by the small-scale farmers. The water consumption of the farmers was assessed through the utilization of Parshall flumes, which are instruments designed to quantify the amount of water in motion. The findings indicated a notable variance between the actual and predicted crop outputs (Fig. 5). The observed yields for plots 1, 2, and 3 were 4.74, 3.97,

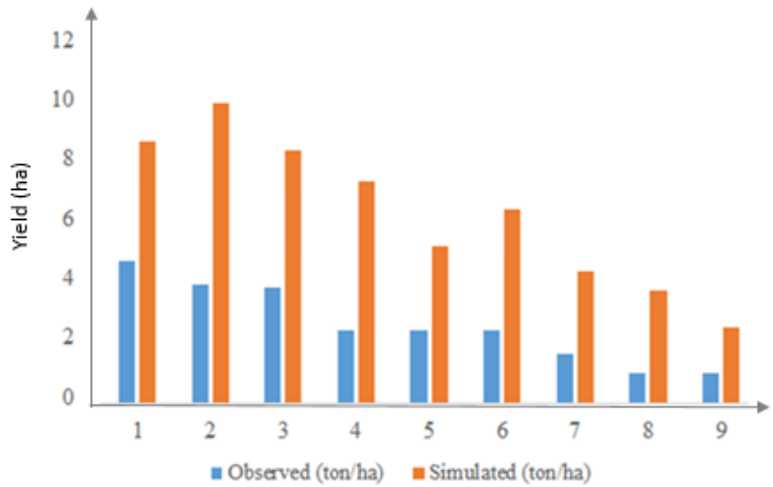


Fig. 5: The simulated and observed potato yield under different treatment

and 3.86 tons per hectare, respectively, whereas the aqua-crop model simulations predicted much higher yields of 8.77, 10.04, and 8.48 tons per hectare for the same plots. The variation in irrigation practices and water management among farmers is the reason for this difference (Teweldebrihan *et al.,* 2024). The model assumes that water is applied consistently based on the scenario selected. Nevertheless, in reality, the irrigation practices of farmers may exhibit less uniformity, potentially leading to inadequate or excessive irrigation in contrast to the simulated scenarios. These inconsistencies may explain the observed yield gap between the model's predictions and the actual crop yields achieved by farmers. Agriculture, being a significant consumer of freshwater worldwide, necessitates the consideration of practical implementation of Water resource management (WRM) strategies on farms (Kamyab *et al.,* 2023). This emphasizes the importance of considering real-world farming practices when interpreting model results.

Aqua-crop simulations reveal factors affecting potato yields

The aqua-crop model simulations provided useful information about factors influencing potato yields. The simulations indicated that regular watering using a comprehensive irrigation system (presumably minimizing water wastage during distribution) led to favorable crop yields. This emphasizes the importance of consistent water delivery for maximum crop yield. Furthermore, the simulations indicated that of 70 percent (%) irrigation efficiency and a 73.4% harvest index (the ratio of harvested product to total biomass) would lead to high yields. It indicates the importance of both efficient water use and good partitioning of resources towards producing harvestable crops (Teweldebrihan *et al.,* 2024). The findings indicate that the disparity in yields between simulated and observed outcomes remains present even when employing a comparable furrow irrigation method (Fig. 6). This differentiation emphasizes the possible influence of variables that are not explicitly considered in the model. One potential factor that could contribute to the differences in yield among smallholder farmers' plots is the variation in soil type. The properties of the soil have a significant impact on the availability of water to plants, and disparities in soil quality may provide an explanation for the observed yield gaps. Another possibility is that the model does not adequately capture the complexities of farmer management practices during the growing season. Consequently, the simulations did not directly incorporate real-world variables like fertilizer application, pest control, and overall crop care, which can all have an influence on crop yield. Despite these differences, the relatively high R-squared value of 0.85 (Fig. 6) indicates a good correlation between simulated and observed yields. This suggests that the aqua-crop model is still useful for understanding the relationships between irrigation practices and

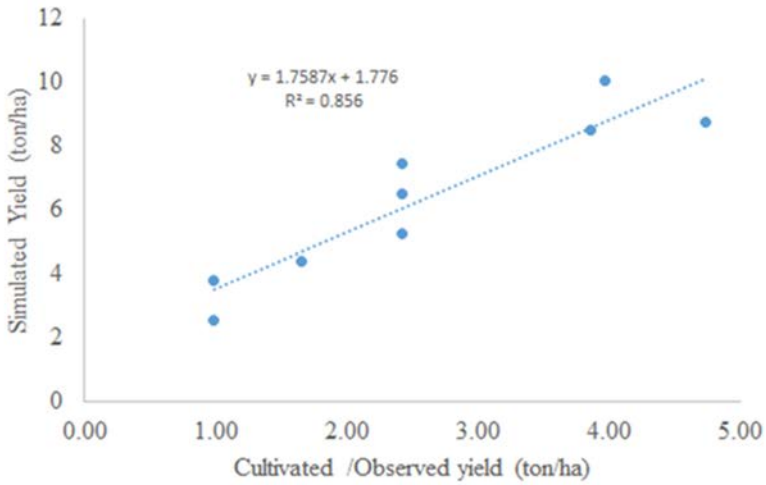


Fig. 6: The comparison between the simulated and observed results of potato yield

crop yields. Aqua-crop is constrained by its limited spatial scale, as it operates under the assumption of a uniform field and disregards any variations that may exist within it. Additionally, the model primarily emphasizes vertical water fluxes while neglecting the lateral movement of water, which can potentially compromise the precision of outcomes in fields characterized by uneven soil properties. While the Aqua-crop model provides useful insights, the results highlight the importance of considering real-world complexities such as soil conditions and farmer management practices when interpreting model outputs and aiming for optimal crop yield. The analysis looked at how irrigation affected crop yield. Full irrigation with good soil fertility produced the highest yield (13.69 tons/ha). The model projected yields that varied from the actual yields observed on real farms, ranging from 3.86 to 4.74 tons per hectare. In order to achieve maximum yields, the model suggests implementing efficient irrigation techniques and maintaining a high harvest index. Upon analyzing the potato crop yields, it was found that soil fertility and irrigation practices had a notable influence on the overall yield outcomes. While full irrigation with unlimited soil fertility resulted in the highest yields, even moderate soil fertility combined with full irrigation produced significant yields. This demonstrates that soil quality is an important factor in crop production, regardless of water availability. The study also indicates that variations in soil characteristics among different farms may account for the disparity in crop yields between the forecasted results of the model and the real harvests of farmers.

The efficiency paradox: high yields vs. water savings in irrigation

The finding highlights the seemingly contradictory finding (high yields with full irrigation vs. higher water efficiency with deficit irrigation). The aqua-crop model simulations provided intriguing insights into the relationship between irrigation practices and water use efficiency. While Fig. 7 indicates that simulated yields were highest in a scenario with effective irrigation application (most likely referring to providing the crop's full water requirement), Fig. 7 shows a contrasting result. The model indicates that evapotranspiration (ET) water, which measures the crop yield per unit of water transpired, exhibited an increase when low irrigation was applied, indicating improved water efficiency under deficit irrigation conditions. Satisfying the entire water demand can lead to higher yields, however, it does not necessarily result in optimal water utilization. Deficit irrigation, inducing water stress, can actually enhance the efficiency of water usage by prompting plants to prioritize biomass production rather than excessive transpiration. This can result in less water used through deficit irrigation, yielding a comparable or even slightly lower crop yield in which the correlation result indicates R^2 of 0.53 (Fig. 7). Nevertheless, a

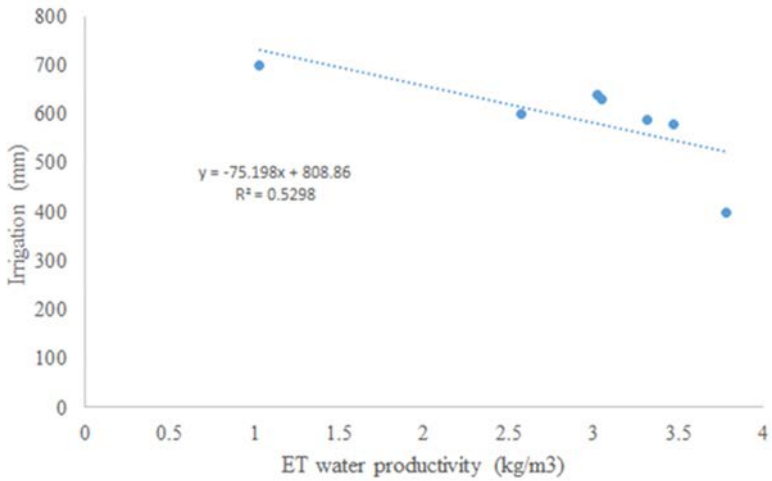


Fig. 7: The comparison between irrigation application and ET water productivity

higher yield of crops per volume of water evaporated (Fig. 7). The finding emphasizes the importance of considering yield and water use efficiency when making irrigation decisions. Farmers can analyze these trade-offs by utilizing the aqua-crop model, a tool that replicates different irrigation scenarios and determines the most effective strategy for optimizing crop yield while also preserving water resources (Teweldebrihan *et al.,* 2024). In water-scarce areas, adopting deficit irrigation as a means to enhance ET water productivity could prove to be a more viable and sustainable approach, despite potentially yielding slightly lower crop outputs compared to full irrigation.

CONCLUSION

The study investigated the effects of irrigation practices, water availability, and soil fertility on crop yields. Although the highest yields were achieved through full irrigation and unlimited soil fertility, further enhancing irrigation practices beyond mere water provision can lead to even greater production. The comparison of real-world and aqua-crop model yields demonstrated the importance of accounting for real-world complexities such as farmer practices and soil conditions. In spite of these distinctions, the model persists as a valuable tool for grasping general irrigation-yield connections. The study also found that, while deficit irrigation may result in slightly lower yields, it can improve water use efficiency by increasing ET water productivity. The significance of taking into account yield and water use efficiency in long-term irrigation decisions, particularly in regions with limited water resources, is underscored by this statement. The aqua-crop model can help farmers explore irrigation strategies that balance crop yield and water conservation. The significance of considering the intricacies of the real world was further highlighted in the study. An examination of crop yields in real-world scenarios, as opposed to the projections made by the aqua-crop model, uncovered certain inconsistencies. This is because the model does not account for all of the variables that influence crop growth in a farmer's field, such as the farmer's specific practices and the soil's unique characteristics. These real-world variations have a significant impact on yields. Despite these limitations, the aqua-crop model is still useful for understanding the overall relationships between irrigation practices and crop yields. The study delved into the notion of deficit irrigation, a water-conservation tactic that entails supplying a quantity of water that is less than the complete requirement of a crop. While this approach may result in slightly lower yields than full irrigation, it can significantly increase water use efficiency. The ET water productivity metric quantifies the crop yield in relation to the water transpired by the plant, indicating the efficiency of water usage in agricultural production. The study emphasizes the importance of taking both yield and water use efficiency into account when making irrigation decisions, especially in water-scarce regions. Farmers can benefit greatly

from the aqua-crop model in this context. Through the simulation of different irrigation scenarios, the model can aid in the formulation of strategies that achieve a harmonious equilibrium between optimizing crop production and preserving essential water sources. This study innovatively explores on how crop yields can be optimized while taking water scarcity into account. It goes beyond simply providing adequate water, demonstrating that strategic irrigation practices can outperform full irrigation in terms of soil fertility. The aqua-crop model, despite its limitations stemming from real-world intricacies, offers valuable perspectives. It indicates that deficit irrigation could enhance water use efficiency, albeit with a minor reduction in yields. This approach is critical in water-scarce regions. The aqua-crop model enables farmers to enhance their decision-making process by providing a platform for them to test various irrigation techniques using simulations. The study proposes the utilization of the aqua-crop model to explore deficit irrigation as a means to enhance water use efficiency, even if it results in slightly lower yields. Additionally, it advocates for the promotion of water-saving practices such as deficit irrigation and recommends policymakers to incorporate the aqua-crop model in irrigation planning for water-scarce areas.

AUTHOR CONTRIBUTIONS

M.D. Teweldebrihan conducted a thorough literature review to gain background knowledge, followed by an initial investigation to get the project started. M.D. Teweldebrihan also collected all of the data, designed the experiment, analysed it to draw conclusions, and wrote the first draft of the manuscript. M.O. Dinka served as a supervisor, review, ensuring the work's accuracy (validation), and contributed to the manuscript preparation process. Finally, M.D. Teweldebrihan edited and formatted the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
Δ	Slope vapour pressure curve
γ	Psychrometric constant
B	Biomass
BMBF	The German Ministry of Education and Research

CC	canopy cover
ET	Evapotranspiration
ETo	Reference evapotranspiration
e_a	Actaul vapour pressure
e.g	Exempli gratia (for example)
e_s	Saturation vapour pressure
FAO	Food and Agriculture Organization
Fig.	Figure
G	Soil heat flux density
GDP	Gross Domestic Product
ha	Hectare
h	Hour
HI	Harvest index
ITCZ	Intertropical Convergence Zone
ETx	Maximum evapotranspiration
ETa	Actual evapotranspiration
Ky	Yield response factor
m	Meter
mm	Millimeter
m/s	Meter per second
m^3/s	Cubic meter per second
mm/y	Millimeter per year
Rn	Net radiation at the crop surface
SG-NAPI	Seed Grant for New African Principal Investigators
T	Mean daily air temperature
Tr	Crop transpiration
TWAS	The World Academy of Sciences
Ton/ha	Ton per hectare
U_2	Wind speed
UNESCO	United Nations Educational, Scientific and Cultural Organization
WP	Water productivity
WRM	water resource management
y	crop yield
y	Year
Ya	Actual yield
Yx	Maximum yields

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