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Water Use of Guinea Grass as Affected by Different Planting Density and Urea Rates Under Rainfed Conditions in Sub-Saharan Africa

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A B S T R A C T

Ongoing efforts are currently being made to rehabilitate drought-affected pastures in Sub-Saharan Africa. One approach being explored is the introduction of non-native grass species, such as *Megathyrsus maximus* (Guinea grass). This study aims to investigate the water use of Guinea grass in semi-arid environments under rainfed conditions. Additionally, it aims to a better understanding of the variability of water use in Guinea grass through the utilization of the Bagging machine learning algorithm. Split-plot field experiments were carried out over two consecutive rainy seasons (2020 and 2021). The treatments included two in-situ rainwater harvesting practices, RWH (ridging plus terracing and terracing alone), three seeding rates, SR (1.5, 2.5, and 3.5 kg ha^{-1}), and two soil nitrogen fertilization rates, SF (95 kg N ha^{-1} and 0 kg N ha^{-1}). These treatments were compared to a control plot that involved zero-tillage, no fertilization, and no rainwater harvesting. The collected datasets were analyzed using R, SPSS 15, and spreadsheets. The results showed significant differences in plant indices and soil moisture content among the treatments. However, the treatments had insignificant effects on seasonal actual crop evapotranspiration (ET_a), which ranged from 1.93 to 3.29 mm day^{-1}. The interactions between SR and RWH were found to have significant impacts on water use. The Bagging algorithm revealed that the variability in ET_a could be attributed to SR (42%), RWH (31%), and SF (26%), respectively. The implementation of rainwater harvesting practices resulted in a significant reduction in water usage, saving 86% of the green water used with a water footprint of 0.25 m^3 kg^{-1}, compared to 1.7 m^3 kg^{-1} for no adoption of RWH conditions. The water use of rainfed Guinea grass was also found highly sensitive to dry spells. Further detailed studies using multiple-layer models are recommended to gain a better understanding of the non-linear interactions in semi-arid environments.

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1. Introduction

The importance of green water (rainwater that is infiltrated into the soil) in achieving sustainable development goals (SDGs), particularly SDG 2 (food security), is widely acknowledged. Nevertheless, efficient use of green water remains a challenging goal that requires significant effort. In arid and semi-arid environments, accurate estimates of crop evapotranspiration (ET_c) are essential for efficient use of green water. ET_c is a term that combines non-productive water use, such as evaporation from the soil surface (E), and productive water use, such as transpiration from plants (T). Equation (1) links ET_c linearly with the climatic water demand (i.e. reference evapotranspiration, ET_o, which is standardized using a hypothetical grass) through a crop

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coefficient (K_c) that varies depending on many factors such as crop type, growth stage, and local conditions, including on-farm water management practices (Allen et al., 1998). Various methods, such as soil water balance, lysimeters, remote sensing algorithms, and sap flows, have been used to estimate ET_c, each with its advantages and disadvantages (Calera et al., 2017; Singh et al., 2019).

Crop evapotranspiration (ET_c) is a measure of the maximum crop evapotranspiration that would occur under ideal conditions, such as no water stress and healthy plants. However, in reality, the actual evapotranspiration (ET_a) is typically lower than ET_c. Although Equation (1) has primarily been used for irrigation management, it can also provide science-based operational guidance for enhancing water use efficiency (WUE) under rainfed conditions. WUE is defined as "*the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop*" (Hatfield and Dold, 2019). It has been suggested that sustainable on-farm practices that increase transpiration (T) while reducing non-productive evaporation (E) can significantly improve crop WUE at the canopy level (Hatfield and Dold, 2019). One promising practice that has shown positive results is rainwater harvesting (RWH). However, the design of RWH systems is critical for maximizing the benefits while minimizing any negative environmental and agricultural impacts (Rahman, 2017).

Rainfed grazing lands play a crucial role in ensuring food security and financial stability. In fact, these lands account for 91% of the livestock production area worldwide (di Virgilio et al., 2019). However, due to frequent droughts, the sustainability of these grazing lands has been severely impacted (Catunda et al., 2021; Chandregowda et al., 2022; Churchill et al., 2022). To combat land degradation, sustainable land management practices have been suggested by the Intergovernmental Panel on Climate Change, IPCC, (2019). In Africa, rainwater harvesting (RWH) systems have been identified as the most suitable method to combat the disappearance of perennial grasses in semi-arid pastures (Mganga et al., 2021). Additionally, to counter the alarming disappearance of some nutritional native pasture species, several countries have introduced exotic nutritious pasture species, such as Guinea grass (Ainsworth and Long. 2021; Benabderrahim and Walid, 2021). Guinea grass is known for its deep root system, high genetic variability C4 plant, and native to tropical conditions (Benabderrahim and Walid, 2021; Soti and Thomas, 2021; Isabel et al., 2021; Deo et al., 2020). Although Guinea grass is tolerant to moderate drought events, it requires a good amount of rainfall (900 - 1500 mm) and is sensitive to waterlogging than deficit conditions (de Oliveira et al., 2022). However, there is a lack of information on the crop coefficients and water use of Guinea grass, especially under rainfed semi-arid conditions. Most of the available estimates are based on irrigation practices (Oliveira et al., 2018; Sanches et al., 2019)

Variability plays a crucial role in various domains, and understanding it is essential for advancing knowledge and making informed decisions. Recent studies have claimed the outperformance of the machine learning algorithms in understanding variability compared to classical methods (Leng and Hall, 2020). Machine learning algorithms build an ensemble decision tree to classify concerned variables via sub-grouping and best-fitting processes (Mupangwa et al. 2020). Ultimately, it reduces the variance and ranks the importance of each variable. To overcome over-fitted model complications associated with machine learning algorithms, variance reduction algorithms like Bagging were developed.

This study was aimed to determine the water use and crop coefficients (Kc) of rainfed Guinea grass as affected by rainwater harvesting (RWH), plant density, and soil fertilization as local conditions in the semi-arid environment in Sudan. The study also employed the Bagging machine learning algorithm to better understand the variability of water use in Guinea grass. These objectives will provide valuable insights into improving water management strategies and sustaining pasture productions in semi-arid regions using non-native species like Guinea grass.

2. Materials and Methods

2.1. Study area

Sudan, an African country located in Sub-Saharan Africa, possesses a vast natural pasture spanning 96 million hectares. The majority of this land, approximately 80%, is situated in arid and semi-arid climates. This extensive pasture plays a crucial role in supporting over 50% of the agricultural sector's contribution to the national gross product (Hussein et al., 2021; Sudan's country report 2015). Primarily consisting of traditional pasture, Sudan heavily relies on livestock breeding, particularly ruminant animals, as a dominant means of livelihood and a vital source of food in the form of meat and milk. However, due to drought conditions, the pastures are currently dominated by low-nutritional quality species with crude protein levels below 8% (Ezzat et al., 2016). This situation is further exacerbated by overgrazing and soil erosion issues. Despite efforts to control grazing (Boke-Olén et al., 2018), pastoralism remains widespread, often leading to the complete destruction of vegetation cover. To mitigate conflicts between grazing and crop farming, the availability of pasture land is limited. Therefore, implementing improved green water management techniques through Rainwater Harvesting (RWH) systems, along with the introduction of scientifically selected moderately drought-tolerant and nutritious fodder grasses like Guinea grass, could have a positive impact on the sustainability of rangelands in Sudan's semi-arid environments. This approach would help conserve water, soil, and plants without causing detrimental effects on the environment (Motta-Delgado et al., 2019).

2.2 Experiment

The experimental site (33.08 ^{0}E and 14.13 ^{0}N) is located in the semi-arid environment, Gezira state, Sudan. Rainfall is seasonal (June – October) of 290 mm (coefficient of variation = 25%), surface air temperature ranges from 21 ^{o}C, to 37 ^{o}C, 21 – 65% for relative humidity (RH), 1.6 – 2.8 m s^{-1} for wind speed at 2 m height, 21.1 – 25.1 MJ m^{-2} day^{-1} for radiation, and 6.4 – 9.8 mm day^{-1} for ET_o. The soil is vertisols where deep cracks develop due to changes in soil moisture contents; topographically, the land is endowed with a gentle slope of 10 cm km^{-1}.

The treatments included two in-situ rainwater harvesting (RWH) practices: ridges plus terracing (RD) and terracing (TR), three seeding rates, SR: 1.5 kg ha^{-1} (SR1.5), 2.5 kg ha^{-1} (SR2.5), and 3.5 kg ha^{-1} (SR3.5), and two nitrogen (urea) soil fertilization rates, SF: 0 kg ha (ZSF) and 95 kg ha (FSF); which were applied as a single dose 21 days after the sowing date in both seasons. These treatments were compared to a control (CT) which consisted of flat, zero-tillage, unfertilized plots without any RWH practices (the common practices in the studied pasture). The selection of RD and TR was based on their popularity and cost-effectiveness in the study area.

A Split-plot Complete Randomized Block design was implemented with three replications (10 m x 10 m per plot) in this study. The main plots consisted of RD, TR, and CT, while the subplots were SR and SF as shown in Figure 1. The experiments were conducted over two rainy seasons, specifically from June to December in the years 2020 and 2021. The experimental sites were prepared in mid-June, with the RD plots undergoing primary plowing using a wide disk plow (20 cm depth), leveling, furrowing using the moldboard (0.8 m apart), and terracing using a disk (30 cm in height). The TR plots were prepared in a similar manner, except for the furrowing practice. Subsequently, Guinea grass seeds were manually spread on July 28th for the first season (June – December 2020) and August 1st for the second season (June – December 2021). At the end of the experiment, Guinea grass was not subjected to any harvesting cycles and grazing was allowed in January.

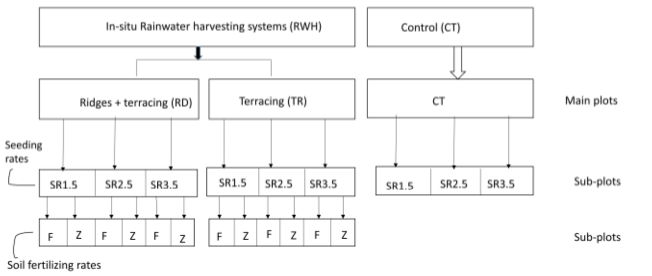

Figure 1. The split-plot experimental design, for studying the impacts of rainwater harvesting, seeding rates and soil fertilization on rainfed Guinea grass, a semi-arid environment, Sudan (2020-2021)

2.3 Data collection

2.3.1 Climatic

A rain gauge was installed at the experimental site to measure daily rainfall. Minimum and maximum surface air temperature, relative humidity, wind speed, and sunshine duration (at 2 m height) were collected from the nearby agrometeorological station, Agricultural Research Corporation, Wadmedani (14.2 ^{o}N and 33.48 ^{o}E),

2.3.2 Agronomic and Soil Moisture Datasets

Field plant and soil samples were collected every ten days over the two seasons. Collected plant indices included height, number of leaves, leaf area index, and fresh and dry biomass; the plant height (cm) was estimated using a tape meter; the leaf area index (m^2 m^{-2}) was directly estimated by multiplying the manually measured area of a single leaf by the number of leaves per square meter; the fresh and dry biomasses were estimated by taking random plant samples from 1 × 1 m^2 per each plot, immediately weighed for estimating the fresh biomass (g $plant^{-1}$); then samples were dried in an oven (70 °C for 24 hrs) and weighed for estimating the dry biomass (g $plant^{-1}$). Estimated biomass was converted to kg ha^{-1} by multiplying the average weight per plant by the average number of plants per unit area (Alebele et al., 2020). these measurements were replicated three times per plot (Yang et al., 2022). The growth stages were determined according to the methodology described by Allen et al. (1998).

Soil moisture contents (0 – 20 cm, 20 – 40 cm, and 40 -100 cm depth) and soil bulk density were measured gravimetrically, i.e. Auger technique, samples were analyzed at the Soil Laboratory of the Faculty of Agricultural Sciences, University of Gezira, Wadmedani, Sudan

2.4 Data analysis

2.4.1 Water use and crop coefficients

The crop evapotranspiration (mm day^{-1}) was estimated using Eq. (1). The reference evapotranspiration (ET_o, mm day^{-1}) was estimated based on the Penman-Monteith model (a short grass approach) (Allen et al., 1998). The actual crop evapotranspiration (ET_a, mm day^{-1}) was estimated using the soil water balance as follows (Eqs. 2 – 10). The water footprint (WFP) was estimated using Eq. (11), as follows:

$$ET_c = ET_o * K_c \quad (1)$$
$$ET_a = P - \Delta\theta - R_o - D_p \quad (2)$$
$$\Delta\theta_v = \theta_{vi} - \theta_{vi+1} \quad (3)$$
$$\theta_g = \frac{w_w - w_d}{w_d} \quad (4)$$
$$\theta_v = \theta_g * \rho_b \quad (5)$$
$$\rho_b = \frac{m_s}{V_t} \quad (6)$$
$$WC = \sum_{i=1}^{j} \theta_{vi} z_i \quad (7)$$
$$DP_i = \begin{cases} 0 & \theta_i \leq \theta_{FC} \\ 1000\,(\theta_i - \theta_{FC}) \end{cases} \quad (8)$$
$$R_o = 2.336 e^{0.504P}, \quad R^2 = 0.90 \quad (9)$$
$$K_c = \frac{ET_c}{ET_o} \quad (10)$$
$$WFP = \frac{ET_c}{DBM} \quad (11)$$

Where, K_c is the crop coefficient (dimension less), and ET_o is the reference evapotranspiration (mm day^{-1}). WFP is the water footprint (m^3 kg^{-1}), and DBM is the dry biomass (kg ha^{-1}); θ_g and θ_v are gravimetric (g g^{-1}) and volumetric (m^3 m^{-3}) soil moisture contents, w_w and w_d are wet and dry weights, respectively, ρ_b is the soil bulk density (g cm^{-3}) , m_s is the soil sample dry weight (g), V_t is the soil sample total volume (cm^3), z is the soil depth (cm), WC is the moisture content at z (cm), P is the rainfall (mm), D_P (mm) is the deep percolation (the groundwater contribution was rendered to zero as the groundwater table is deep of > 15 m); R_o is the runoff volume (10^{-6} m^3), and P is the rainfall event in m^3 (rainfall depth (m) * catchment area (m^2)), which was applied only for estimating runoff amounts under the CT treatments, developed by Shamseddin et al. (2014) for the studied area, i.e. R_o was rendered to zero under RWH practices as terraces were mainly constructed to prevent runoff running outside the boundaries. Equation (12) is a commonly used RWH design model for agricultural purposes (Critchley et al., 1991).

$$\frac{Ca}{Cu} = \frac{CWR - R}{R * Ro * Ef} \quad (12)$$

Where, Ca is the catchment area, Cu is the cultivated area, CWR is the crop water requirements, R is the design rainfall, Ro is the runoff coefficient, and Ef is the efficiency factor of the system. Eq. (1) provides good estimates of CWR.

2.4.2 Statistical analysis

The statistical analysis was conducted using SPSS 15.0. The null hypothesis stated that none of the treatments and their interactions would improve the water use of rainfed Guinea grass in a semi-arid environment. Descriptive statistics were used to summarize the measured datasets. The analysis was based on the general linear model (GLM) with the full factorial model, and the Bonferroni test was used for post hoc multiple comparisons of observed means (P = 0.05). The dependent variables included a set of measured plant and soil indices, while the independent variables were RWH, SR, SF, and season. A one-factor analysis of variance was used to assess the comparisons for observed means of soil fertilization and season, as the groups were less than three, which is a requirement for the Bonferroni test.

In order to better understand the variability in ETa, the Bagging machine learning algorithm was applied. The decision tree was built using the "ANOVA" method from the "rpart" package in R software (version 4.2.2). The dataset was divided into 70% for model training and 30% for testing. The Bagging algorithm generated the ensemble mean from 10 cross-validated regression models. The performance metric used to evaluate the models was the root mean square error (RMSE).

3. Results and Discussion

3.1. Water use of rainfed Guinea grass

3.1.1 impacts of rainwater harvesting

Table (1) presents a summary of the estimated ET_a (actual crop evapotranspiration) of rainfed Guinea grass in the semi-arid environment of Sudan, considering the impact of RWH practices (RD and TR treatments). The seasonal ET_a values for RD, TR, and CT were 2.7 mm day^{-1}, 2.9 mm day^{-1}, and 2.5 mm day^{-1}, respectively. These values are 27-37% lower than the estimate of 3.99 mm day^{-1} for subtropical conditions by Sanches et al. (2019). While the applied RWH techniques significantly increased the seasonal soil moisture content by 37-97% for RD and 42-84% for TR compared to the control (CT), there was no significant difference in the seasonal ET_a between RWH practices and CT. However, the seasonal ET_a of CT was generally 8%-18% lower than that of RWH treatments (RD and TR).

The concept of water use efficiency (WUE) establishes a linear relationship between biomass production and water use, indicating that the higher ET, the higher biomass production. This explains the higher biomass production observed with RWH treatments compared to CT (Table 1). Consequently, the implementation of RWH practices maximized consumptive water use (T) at the expense of non-consumptive water use (E). This finding aligns with the reported increase in maize biomass without a change in water use by Hatfield and Dold (2019). RWH practices achieved this by increasing soil moisture content, which in turn promoted plant canopy development, reducing the exposed surface area for evaporation and improving plant-soil water interactions. Additionally, RWH practices allowed for more infiltration time for harvested runoff; in heavy clayey soils, decreased soil bulk density due to increased soil moisture, creating favorable conditions for root system growth and interaction. Furthermore, the improved leaf area index (LAI) resulting from RWH practices will have a substantial impact, as evaporation losses were exponentially related to LAI (Eq.13).

$$E = ET_o * e^{-0.39LAI} \quad (13)$$

According to eq. (13), the presented LAI values in Table (1) estimated the seasonal evaporation losses (E) at 0.01 – 0.7 mm day^{-1}, 0.03 – 1.01 mm day^{-1} for the TR, and 2.35 – 3.61 mm day^{-1} for the CT.

Table 1. Growth and water use of rainfed Guinea grass as affected by two in-situ rainwater harvesting systems (Ridges plus terracing, RD, and Terracing, TR) over two experimental seasons, compared to a control CT (flat, zero tillage, unfertilized without rainwater harvesting plots), the semi-arid environment, Sudan

Index	RD	TR	CT
		Season 1	
Plant height (cm)	41^a	41^a	13^b
Leaf number (number)	17^a	16^a	10^a
Fresh biomass (t ha^{-1})	8.7^a	8.5^a	1.2^b
Dry biomass (t ha^{-1})	2.2^a	2.1^a	0.3^b
Leaf area index (m^2 m^{-2})	1.7^a	1.3^a	0.09^a
Soil moisture (mm)	207^a	193^a	144^b
Soil bulk density (g cm^{-3})	0.9^a	1.03^a	1.11^b
Crop evapotranspiration (mm day^{-1})	2.96^a	3.29^a	3.02^a
		Season 2	
Plant height (cm)	43^a	42^a	18^b
Leaf number (number)	16^a	16^a	10^a
Fresh biomass (t ha^{-1})	9.2^a	9.2^a	2.7^b
Dry biomass (t ha^{-1})	2.3^a	2.3^a	2.0^a
Leaf area index (m^2 m^{-2})	0.5^a	0.4^a	0.2^a
Soil moisture (mm)	144^a	149^a	105^b
Soil bulk density (g cm^{-3})	0.84^a	0.86^a	0.96^b
Actual crop evapotranspiration (mm day^{-1})	2.37^a	2.54^a	1.93^a

Different letters mean the difference is significant (P = 0.05)

During the two experimental seasons, the rainfall amounts were 262 mm and 252 mm for the first and second seasons, respectively. These amounts accounted for 92% and 90% of the normal rainfall. However, the results presented in Table (1) indicated significant differences in ET_a between the two seasons, with the first season had the higher ET_a values, with increases of 25%, 30%, and 56% for RD, TR, and CT, respectively. This was also accompanied by better soil moisture content and leaf area index (LAI) compared to the second season, as shown in Table 1. The variation in water use between the seasons can be mainly attributed to the distribution of rainfall rather than the actual amounts received. The second season experienced longer dry spells, with an average of 7.2 days with rainfall less than 1.0 mm, compared to 3.4 days in the first season.

3.1.2 Planting density

Table (2) presents a comparison of the estimated ET_a influenced by plant density, specifically three seeding rates (SR1.5, SR2.5, and SR3.5). In terms of statistical significance, the applied seeding rates had minimal effects on all measured properties, except for the soil moisture content and soil bulk density during the first season. Ding et al. (2015) suggested a multi-layer model as a replacement for the single-layer model (such as Penman-Monteith) to gain a better understanding of the non-linear interactions between microclimate and crop physiology. Consequently, more detailed studies based on a multi-layer model are necessary to comprehend the non-linear interactions between seeding rates and water usage of Guinea grass in semi-arid environments. In general, a lower seeding rate results in higher water use (ET_a) for Guinea grass, while a higher seeding rate leads to increased biomass production. The lowest applied seeding rate (SR1.5) is associated with the lowest LAI, indicating relatively its higher evaporation losses compared to SR2.5 and SR3.5 treatments.

Table 2. Growth and water use of rainfed Guinea grass as affected by three seeding rates, SR (1.5, 2.5, and 3.5 kg ha^{-1}) over two experimental seasons in a semi-arid environment, Sudan

index	SR1.5	SR2.5	SR3.5
		Season 1	
Plant height (cm)	51 ^{a}	52 ^{a}	47 ^{a}
Leaf number (number)	29 ^{a}	30 ^{a}	28 ^{a}
Fresh biomass (t ha^{-1})	10.4 ^{a}	11.8 ^{a}	12.2 ^{a}
Dry biomass (t ha^{-1})	3.3 ^{a}	3.4 ^{a}	3.8 ^{a}
Leaf area index (m^{2} m^{-2})	3.5 ^{a}	4.3 ^{a}	3.8 ^{a}
Soil moisture (mm)	193 ^{a}	190 ^{a}	141 ^{b}
Soil bulk density (g cm^{-3})	0.98 ^{a}	1.01 ^{b}	1.02 ^{b}
Crop evapotranspiration (mm day^{-1})	2.84 ^{a}	2.75 ^{a}	2.66 ^{a}
		Season 2	
Plant height (cm)	18 ^{a}	17 ^{a}	16 ^{a}
Leaf number (number)	7 ^{a}	7 ^{a}	7 ^{a}
Fresh biomass (t ha^{-1})	2.8 ^{a}	2.9 ^{a}	3.1^{a}
Dry biomass (t ha^{-1})	2.5 ^{a}	2.6 ^{a}	2.9 ^{a}
Leaf area index (m^{2} m^{-2})	0.05 ^{a}	0.05 ^{a}	0.05 ^{a}
Soil moisture (mm)	147 ^{a}	138 ^{a}	103 ^{b}
Soil bulk density (g cm^{-3})	0.87 ^{a}	0.87 ^{a}	0.87 ^{a}
Actual crop evapotranspiration (mm day^{-1})	2.59^{a}	2.64 ^{a}	2.51 ^{a}

3.1.3 Soil fertilization

Table 3 presents the findings of a study conducted in Sudan, which examined the effects of soil fertilization on Guinea grass in semi-arid environments. The study compared two different soil fertilization rates, 95 kg N ha^{-1} and 0 kg N ha^{-1}, and found that there were no significant differences between the two rates, except for the soil moisture during the second season. Therefore, the impact of soil fertilization on the seasonal water use of Guinea grass was found to be insignificant (Table 3). These findings contradict the results of a study conducted in Brazil by Maués Macedo et al. (2022), who indicated a positive correlation between fertilization (160 - 200 kg N ha-1) and ET_c of Guinea grass based on a principal component analysis of data collected from various rainfed and irrigation trials.

The optimal seeding rate for Guinea grass under rainfed conditions is not well-documented, with only one experimental seeding rate of 40-45 pure seeds m^{-2} reported by Maués Macedo et al. (2022). In Sudan, it is common to practice zero soil fertilization for both pasture and crop farming. However, due to increasing soil degradation rates, a minimum amount of nitrogen might be necessary.

Santos et al. (2012) suggested that the growth and productivity of Guinea grass in pastures were dependent on nitrogen supply, while Paciullo et al. (2016) highlighted the uncertainty surrounding the relationship between production and fertilization of Guinea grass. Maués Macedo et al. (2022) recommended a nitrogen dose of 200 kg N ha^{-1} for Guinea grass grown under fully rainfed conditions in Brazil.

Table 3. The effects of soil fertilization on rainfed Guinea grass over two experimental seasons, semi-arid environments, Sudan

index	Fertilized	Unfertilized
Season 1		
Plant height (cm)	58 ^{a}	44 ^{a}
Leaf number (number)	32 ^{a}	26 ^{a}
Fresh biomass (t ha^{-1})	133 ^{a}	92 ^{a}
Dry biomass (t ha^{-1})	33 ^{a}	36 ^{a}
Leaf area index (m^2 m^{-2})	4.7 ^{a}	3.1 ^{a}
Soil moisture (mm)	194^a	189 ^{a}
Soil bulk density (g cm^{-3})	1.0 ^{a}	1.0 ^{a}
Crop evapotranspiration (mm day^{-1})	2.7 ^{a}	2.6 ^{a}
Season 2		
Plant height (cm)	18 ^{a}	16 ^{a}
Leaf number (number)	7 ^{a}	6 ^{a}
Fresh biomass (t ha^{-1})	32 ^{a}	26 ^{a}
Dry biomass (t ha^{-1})	32 ^{a}	23 ^{a}
Leaf area index (m^2 m^{-2})	0.06 ^{a}	0.04 ^{a}
Soil moisture (mm)	148 ^{a}	127^b
Soil bulk density (g cm^{-3})	0.86 ^{a}	0.87 ^{a}
Actual crop evapotranspiration (mm day^{-1})	2.6 ^{a}	2.5^a

Same letters mean the difference is insignificant (P = 0.05)

3.1.4 Seasonal effects

Table (4) presents a summary of the effects of different seasons on the growth of Guinea grass in a rainfed semi-arid environment. The findings indicate that the season has a significant influence on rainfed Guinea grass, with the exception of dry biomass production and water use. The first season stands out as it demonstrates favorable indices due to well-distributed rainfall, although the soil bulk density decreases by 13% in the second season. This decrease suggests that the continuous growth of Guinea grass positively affects the soil's hydrological conditions, leading to an increase in infiltration rate as the soil bulk density decreases. On the other hand, the impact of the season on the growth of Guinea grass under wet conditions is insignificant, as stated by Pezzopane et al. (2017).

Table 4. seasonal impacts on selected plant, soil and water use of Guinea grass grown under a semi-arid environment Sudan (2020 – 2021)

Index	Season 1	Season 2
Plant height (cm)	53^a	18^b
Leaf number (number)	30 ^{a}	7 ^{b}
Fresh biomass (t ha^{-1})	11.6 ^{a}	2.9 ^{b}
Dry biomass (t ha^{-1})	3.4 ^{a}	2.9 ^{a}
Leaf area index (m^2 m^{-2})	4.2 ^{a}	0.05 ^{b}
Soil moisture (mm)	194 ^{a}	135 ^{b}
Soil bulk density (g cm^{-3})	0.99 ^{a}	0.86 ^{b}
Actual crop evapotranspiration (mm day^{-1})	2.73 ^{a}	2.48 ^{a}

3.1.5 Interactions

The effects of interactions between treatments on various parameters were studied using linear multivariate models. Results were presented in Table (5). The results state that: firstly, the intercepts of the models are significant and of high values, suggesting that either the interactions are non-linearly controlled or there is a need to consider more explanatory variables. Secondly, the RWH*SR interaction has no significant effects, except for the soil moisture contents during the first season (S1SM). Thirdly, the RWH*SF interaction only affects significantly the soil bulk density of the first season (S1BD). Fourthly, the SR*SF interaction showed insignificant effects. Finally, the RWH*SR*SF interactions have significant impacts on all indices, except for the LAI during the second season (S2LAI), actual crop evapotranspiration during the first season ($S1ET_a$), the seasonal soil moisture content (S1SM and S2SM), and the soil bulk density of the second season (S2BD). Also, the trend of the significant effects of the RWH*SR*SF interactions are seasonally consistent on leaf height, leaf number, and the production of fresh and dry biomass (Table 5). Consequently, the treatments as local conditions presented statistically varied results. Relative to the soil fertilization, planting density (SR) and water supply (RWH) as local conditions play a crucial role in sustaining Guinea grass under rainfed conditions of semi-arid environments. Generally, the treatments RDSR1.5Z, TRSR1.5Z, TRSR1.5Z, TRSR2.5F, TRSR1.5Z, RDSR1.5Z, CTSR1.5Z, and TRSR1.5Z were associated with the highest recorded values for plant height, leaf number, fresh biomass, dry biomass, leaf area index, soil moisture content, soil bulk density, and ET_a of rainfed Guinea grass, respectively.

Table 5. Effects of treatments' interactions on Guinea grass under rainfed conditions of semi-arid environments, based on multivariate models. The treatments were rainwater harvesting (RWH), Seeding rate (SR), and soil fertilization (SF). The dependent variables were season (S), selected plant indices (leaf height, H, leaf number, LN, fresh biomass, FBM, dry biomass DBM, and leaf area index LAI), soil indices (moisture content, SM, and bulk density, BD), and actual crop evapotranspiration (ET_a)

index	intercept	SR*RWH	SR*SF	RWH*SF	RWH*SR*SF
S1H	78,037*	501.278	156.874	5.567	5.037*
S2H	89,854*	648.178	168.206	0.254	0.330*
S1LN	15,797*	411.704	103.998	7.211	22.354*
S2LN	14,719*	118.155	44.758	1.523	3.536*
S1FBM	290,486*	1,774.62	1,199.26	5.85	28.261*
S2FBM	384,401*	2,872.18	1,779.05	77.898	143.889*
S1DBM	18,486*	112.221	64.984	0.821	2.193*
S2DBM	38,551*	220.948	135.074	3.86	8.444*
S1LAI	92*	1.499	1.464	0.201	0.424*
S2LAI	10*	0.098	0.054	0.003	0.055
S1ETc	646*	9.668	3.852	0.013	5.74
S2ETc	351*	2.438	1.615	0.014	0.158*
S1SM	1,223,845*	8,059*	325.545	214.437	876.058
S2SM	2,242,302*	258.654	4.251	46.962	713.909
S1BD	67*	0.017	0.002	0.014*	0.0003*

* indicates significant at P = 0.05

3.1.6 A stepwise regression modeling and Bagging algorithm

The collected indices, including plant height, leaf number, biomass, leaf area index, soil moisture, and bulk density, were used to stepwise regress the ET_a (dependent variable). The resulting model indicated that the soil moisture content (SM) was the only significant variable (Eq. 14), highlighting the crucial role of implementing RWH for sustaining Guinea grass under rainfed conditions. To evaluate the performance of the model in predicting ET_a, Fig. (2) was utilized. The model generally underestimated ET_a, with a root mean square error (RMSE) of 1.69 mm day^{-1}, and could only explain 20% of the variability in ET_a (Fig. 2).

$$ET_a = -2.034 + 0.025 * SM \quad R^2 = 0.20 \quad (14)$$

Fig. (3) displays the decision tree that was built using the Bagging algorithm. The decision tree exhibited RMSE values of 1.49 mm day^{-1} for the training dataset and 1.46 mm day^{-1} for the validation dataset, with an overall average ET_a (for all treatments) of 2.4 mm day^{-1}. The variable importance analysis revealed that the SR treatment is responsible for 42% of the variability in Guinea grass water use, followed by RWH at 31%, and SF at 26%. Consequently, SR had the most significant impact on ET_a, followed by RWH and SF. The RWH practices (RD and TR) resulted in relatively higher water use (2.5 mm day^{-1}) compared to the CT (2.2 mm day^{-1}). The highest and lowest ET_a values were observed in the RDSR3.5F and RDSR1.5Z treatments, with values of 3.0 mm day^{-1} and 1.7 mm day^{-1}, respectively. These findings partially contradicted the results obtained from the classical statistical analysis presented in Table (5), where the highest ET_a (3.8 mm day^{-1}) was achieved by the TRSR1.5Z treatment, and the lowest one (2.2 mm day^{-1}) by the RDSR1.5F treatment.

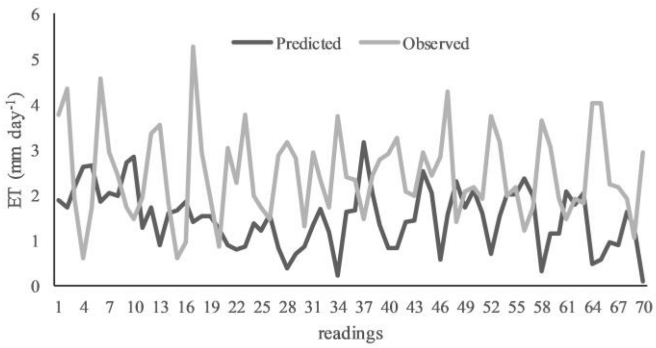

Figure 2. The performance of a stepwise regression model for predicting crop evapotranspiration (ET_a) of Guinea grass, under rainfed conditions enhanced by in-situ rainwater harvesting practices, the semi-arid environment in Sudan. The estimated root mean square error is 1.69 mm a day

3.2 Crop coefficients (K_c) of rainfed Guinea grass

Table (6) presents the average Kc values for rainfed Guinea grass cv. Mombasa during the experimental seasons. The Kc values for the RWH treatments (RD and TR) were significantly different from the CT values. For the initial, development, midseason, and late stages, the Kc values were 0.19, 0.26, 0.98, and 0.49 for the RWH treatments, compared to 0.66, 0.43, 0.60, and 0.36 for the CT, respectively.

Table (6) Estimated crop coefficients of rainfed-based *Guinea grass* cultivated under two in-situ rainwater harvesting practices (ridging plus terracing, RD, and terracing, TR), and three seeding rates, SR (SR15 for 1.5 kg ha^{-1}, SR25 for 2.5 kg ha^{-1}, and SR35 for 3.5 kg ha^{-1}), compared to the control, CT (flat, zero-tillage plots), the semi-arid environment, Sudan. Averages of two experimental seasons were presented (2020 – 2022)

Growth Stage	RD	TR	CT
		SR1.5	
initial	0.14	0.31	0.60
development	0.24	0.30	0.42
mid	0.93	0.93	0.69
late	0.37	0.62	0.32
		SR2.5	
initial	0.33	0.23	0.61
development	0.35	0.24	0.40
mid	1.04	0.75	0.56
late	0.45	0.42	0.33
		SR3.5	
initial	0.17	0.32	0.77
development	0.21	0.29	0.46
mid	0.82	0.77	0.55
late	0.54	0.38	0.44

The Kc values for the CT during the initial and development stages were higher than those of the RWH treatments due to higher evaporation rates during these early growth stages. However, when the plants reached the midseason and late growth stages, the transpiration part became dominant following the increased soil moisture content resulting from the RWH practices. During the early stages, the K_c values were influenced by the wetted exposed area to evaporation, which decreased as the canopy increased. Despite similarities in the wetted exposed areas to evaporation for RD, TR, and CT, the RWH practices significantly improved the hydrological conditions of the soil, as evidenced by the reduction in soil bulk density. The RWH treatments showed reductions of 11.7% - 15.5% in soil bulk density compared to the CT. This reduction allowed for more infiltrated rainwater under the RWH treatments. However, Fig. (4) indicates that ET_a tends to increase as the soil bulk density increases. This is because rainwater takes longer to infiltrate in poor surface soil hydrological conditions caused by increased soil bulk density, especially during the initial and development stages. This explains the 59% difference in K_c values between the RWH practices (K_c = 0.22) and the CT (K_c = 0.54) for the initial and development growth stages, on average.

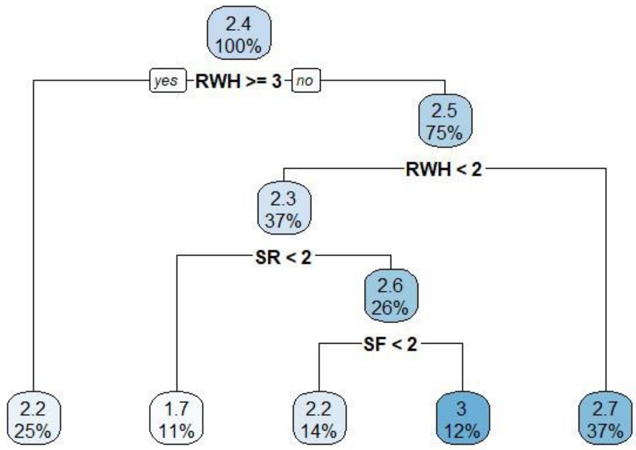

Figure 3. A developed decision tree showing how the variability of the seasonal crop evapotranspiration of rainfed Guinea grass (mm day^{-1}) as affected by rainwater harvesting (RWH), seeding rate (SR), and soil fertilization (SF). The RWH consisted of three levels: ridging plus terracing (1), terracing (2), and control (3); three levels for SR: 1.5, 2.5, and 3.5 kg ha^{-1}; two levels for SF; 95 kg N ha^{-1}, and 0 kg N ha^{-1}. The general mean is 2.4 mm day^{-1}. If the condition is true take the left, otherwise, take the right.

The average K_c values for the initial and midseason growth stages of rainfed Guinea grass were 8% - 62% lower than values reported for irrigated subtropical conditions by Sanches et al. (2019) and de Oliveira et al. (2018). The initial K_c is primarily influenced by the number of wetting events received (Allen et al., 1998), with the crop ET being mainly affected by direct evaporation from the soil surface. As the wetting of the soil surface increases following rainfall events, the evaporation also increases, resulting in significant differences in the initial Kc values between semi-arid and subtropical conditions where rainfall amounts are higher. On the other hand, the midseason K_c is mainly influenced by prevailing weather conditions and crop characteristics such as relative humidity, wind speed, and crop height (Allen et al., 1998). It is important to note that the steward structure parameters of Guinea grass are significantly influenced by the harvesting time. The study by Sanches et al. (2019) aimed to simulate rotational grazing systems with a pre-established residue height of 30 cm for Guinea grass, while our study had no-cutting cycles with a peak height of 172 cm. These differences. justify the slight variations in the peak K_c values between our study and Sanches et al. (2019). Additionally, despite the insignificant differences in seasonal rainfall amounts, the seasonal K_c varied significantly between the first and second seasons. This indicates the significant impact of dry spells on K_c, with longer dry spell lengths in the second season resulting in a lower Kc value. These dry spells also had a significant impact on the seasonal leaf area index (LAI). Singh et al. (2019) have found a strong exponential relationship between the Kc of wheat and its LAI. Lastly, the different applied seeding rates (SR) did not show any significant effects on the seasonal K_c averages. however, the seasonal K_c increases generally as the seeding rate increases, except for the SR3.5. This holds also for the effect of the applied soil N fertilization. This is well-agreed with the result of Lamede et al. (2021) who claimed the insignificant impacts of the nitrogen fertilization on the percentages of leaves of *Guinea grass.*

3.2 Water use efficiency of rainfed Guinea grass

The water footprint, WFP, is used to measure the water use efficiency of Guinea grass. This indicator takes into account both biomass production and ET_a. In Tables (1 through 5), we can see how biomass production is influenced by various factors such as rainwater harvesting (RWH), seeding rate (SR), seedling fertilizer (SF), and the season. The implementation of RWH practices has had a significant impact on biomass production, increasing average soil moisture contents by 35% - 48% compared to conventional tillage (CT). As a result, the production of fresh biomass has increased by 341% - 381% compared to CT. While the seeding rate did not have a significant effect on biomass production, the highest seeding rate of 3.5 kg ha^{-1} did result in the highest biomass production. The season also plays a role, with the first season showing higher biomass production compared to the second season. It is important to note that RWH practices were implemented to minimize seasonal differences in soil moisture contents compared to CT. Therefore, when designing RWH practices for establishing Guinea grass in arid and semi-arid environments, it is crucial to consider the detrimental effects of dry spells.

Table (7) presents a comparison of the estimated water footprint (WFP) of rainfed Guinea grass in the semi-arid environment of Sudan, based on dry biomass production. The seasonal WFP for the RWH treatments is calculated to be 0.25 m^3 kg^{-1}, whereas for the CT, it is 1.72 m^3 kg^{-1} on average. This indicates that RWH systems require only 0.25 m^3 of water to produce one kilogram of dry biomass, while the CT conditions require six times more water to produce the same amount of biomass. In other words, RWH systems have managed to save 86% of the green water consumption of rainfed Guinea grass in the semi-arid environment. The estimates of WFP also reveal slight seasonal differences, with 0.22 m^3 kg^{-1} for the first season and 0.27 m^3 kg^{-1} for the second season. These differences can be attributed to variations in dry spells. As the duration of dry spells increases, water consumption also increases, resulting in lower biomass production and ultimately, relatively poor water use efficiency.

4. Conclusion

1. Rainfed pastures play a crucial role in ensuring food security and financial stability in semi-arid environments.
2. However, the occurrence of frequent droughts has significantly hindered the effectiveness of these pastures. To address this issue, there has been a growing trend of using exotic nutritive and drought-tolerant species like Guinea grass to improve degraded pastures.
3. Most studies on Guinea grass, however, have focused on irrigation-based approaches. Nevertheless, the introduction of Guinea grass into rainfed semi-arid environments has been positively influenced by the implementation of cost-effective in-situ rainwater harvesting (RWH) practices.
4. RWH practices have yielded encouraging results in conserving three essential resources for semi-arid pastures, namely green water, soil hydrological condition, and vegetation biomass production. By diverting non-productive water uses such as evaporation towards productive ones like transpiration, the applied RWH packages have significantly enhanced the water use efficiency of rainfed-based Guinea grass.
5. Seasonal actual crop evapotranspiration (ET_a) rates under ranfed conditions enhanced with RWH practices were ranged from 1.93 to 3.29 mm day^{-1}. The estimates obtained from this research will aid in the sustainable design of RWH systems for establishing Guinea grass under rainfed conditions.
6. The importance of considering the negative effects of dry spells on water usage and

7. biomass production cannot be underestimated when designing RWH systems
8. Seeding rates have the most significant impacts on variations in ET_a, followed by RWH, and fertilization.
9. The importance of considering the negative effects of dry spells on water usage and biomass production cannot be underestimated when designing RWH systems.
10. The conclusions drawn from this study, which also examined the impact of different seeding rates and nitrogen fertilization on Guinea grass, were limited due to the use of linear models. Therefore, it is crucial to conduct more detailed studies using multiple-layer models to gain a better understanding of the non-linear interactions that occur in arid and semi-arid environments.

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