Global Scientific JOURNALS

GSJ: Volume 10, Issue 4, April 2022, Online: ISSN 2320-9186

www.globalscientificjournal.com

Maize Yield and Water Productivity under Strategic Supplemental Deficit Irrigation during short rainy seasons

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Abstract

Irrigation can mitigate the agricultural production challenge of erratic and unpredictable precipitation in sub-Saharan Africa (SSA). However, improving water productivity (WP) in irrigation sector will reduce the already intensified competitions to water resource. The question remains on how to manage supplemental irrigation in light of the temporal distribution of seasonal precipitation, aiming at improving crop yield and WP. Literature recommends deficit irrigation practices; however, its use as supplemental irrigation is still not well understood. In this context, a study in Tanzania evaluates the WP of maize with deficit supplemental irrigation (DSI). A CROPWAT model calculates the irrigation water requirements (IWR) for different levels (treatments) and for scheduling. Treatments were 60, 40, 20, and 0 percent deficits of the actual supplemental IWR, respectively. The results show that soil moisture dynamics reflect the water application levels with moisture readings increasing with water applications. The trend is also reflected with higher yields of maize biomass and grain under full supplemental irrigation (FSI) application than under DSI. The DSI embraced advantages of higher biomass production per unit of water used, while FSI resulted in higher grain yields per unit of water used. Therefore, the decision to apply DSI or FSI in SSA relies on production aims, land availability, and the level of understanding of the farmers of these two competing advantages.

Keywords: CROPWAT; deficit supplemental irrigation; drip irrigation; maize yield; water productivity; Tanzania

1. Introduction

Fresh water scarcity is a global concern; therefore, its efficient use in all big water usage sectors is inevitable (Abdalhi et al., 2016; Mohanty et al., 2013; Pereira et al., 2009). Estimated to make up 80% of withdrawals, most water withdrawals are for irrigated agriculture (Liu et al., 2017). Agriculture experiences significant challenges in its effort to feed the growing population (Godfray et al., 2010; Mutiro et al., 2006; Webber et al., 2006). Aggravated by climate change and soil degradation, the need for fresh water in agricultural production will only continue to increase as the world population increases (El Solh and Awawdeh, 2014; Madramootoo and Fyles, 2010).

In particular, in sub-Saharan Africa (SSA), high population growth and food demand is expected to increase water needs for agriculture. Production of food crops using irrigation is expanding since major staple food crops in SSA are severely affected by droughts and unreliable rainfalls (Munishi et al., 2015; Rowhani et al., 2011). Farmers often lose their harvests, subsequently experiencing severe food shortages and poverty (Graef and Haigis, 2001; Silungwe et al., 2019). Irrigation is an alternative strategy suggested to insure against uncertain rainfall and drought in agricultural productions, thus improving crop yields (Cavero et al., 2012; Chauhan et al., 2015; Muchapondwa, 2015; Woli et al., 2012). So far, few areas in SSA use irrigation and their respective water use efficiencies are very low. In Tanzania, for instance, irrigation is used on less than 1% of the total potential area for irrigation, which is 29.4 million ha (URT, 2010); this is despite massive advocacy in favor of irrigation investments (URT, 2010). This trend is common across many SSA countries; however, for sustainable irrigation, advocacy should also incorporate means of improving water use efficiency for rainfed, irrigated, and supplemental irrigation agriculture. Different studies insist that the shortage of irrigation water will accelerate; thus, under irrigation, measuring the production per unit of water, rather than the production per unit area, must be emphasized (Fereres and Soriano, 2007; Howell, 2001).

Methods for improving crop water productivity must be sufficiently robust and sustainable to accommodate irrigated agriculture (including supplemental irrigation), and rainfed agriculture. By definition, water productivity (WP), or water use efficiency, is a physical mass of production or the economic value of production per unit volume of water (Molden, 1997). Normally, WP is measured against gross or net inflow, depleted water, process depleted water, or available water" (Molden, 1997). Supplementing irrigation, while considering the temporal distribution of seasonal precipitation is key for improving crop yields and water productivity (WP) due to limited water resources. The literature also recommends deficit irrigation practices for improving on-farm WP (Fereres and Soriano, 2006; Geerts and Raes, 2009; Pandey et al., 2000); however, information on its use as supplemental irrigation is limited. In this context, a field study was conducted in sub-humid Tanzania to evaluate the WP of maize, with supplemental deficit irrigation, during short rain seasons with treatments representing 60%, 40%, 20%, and 0% deficits of irrigation water requirements after subtracting rainfall (supplemental irrigation). More specifically, the study aimed (i) to investigate the growth performance of maize under supplemental deficit irrigation and its associated WP values at different stages; (ii) to determine the level of supplemental deficit irrigation that gives the highest water productivity of maize at maturity; and (iii) to extrapolate the possibility of when and where deficit irrigation could be useful in improving production per unit volume of water.

2. Materials and methods

2.1. Study area description

Experiments were conducted at the crop museum of the Sokoine University of Agriculture (SUA), Morogoro Region, Tanzania (Fig. 1). The region is located between latitude 5^o 58" and 10^o 0" South and longitude 35^o 25" and 38^o 30" East, with an average elevation of about 526 m above mean sea level. The area receives bimodal rain, with an average annual rainfall of 830 mm. The short rains occur between November and January and are locally known as ‘Vuli’, followed by long rains between March and June, locally known as ‘Masika’. A dry spell is experienced in February. Figure 2 shows the summary of average weather parameters between 1980 and 2010 based on data provided by the Tanzania Meteorological Agency located at Sokoine University of Agriculture (SUA). An automatic weather station was installed directly at the trial site for measuring daily temperature, precipitation, relative air humidity, and global solar radiation.

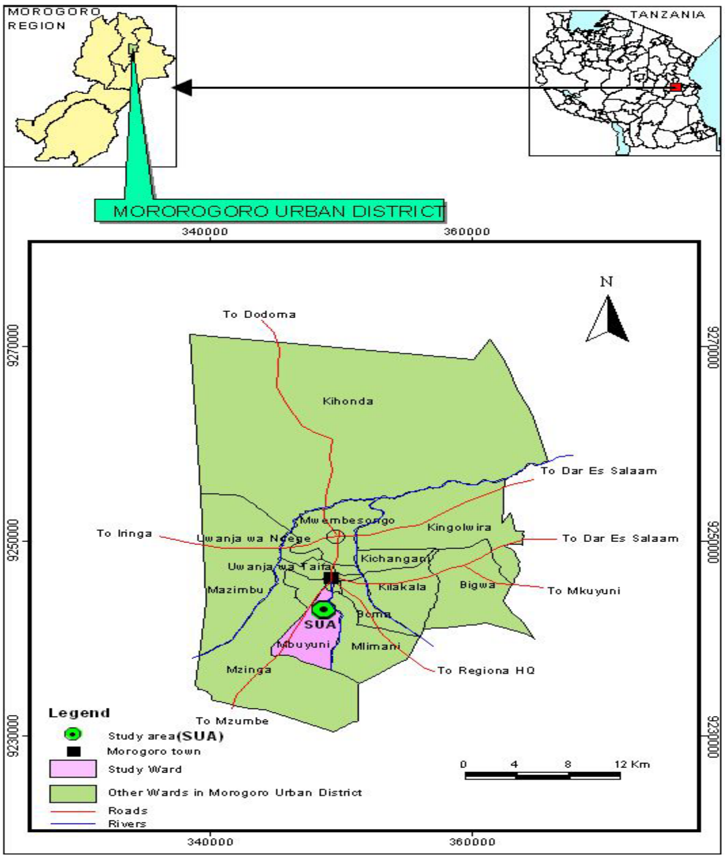


Figure 1: Map showing the trial site at SUA, Morogoro, Tanzania.

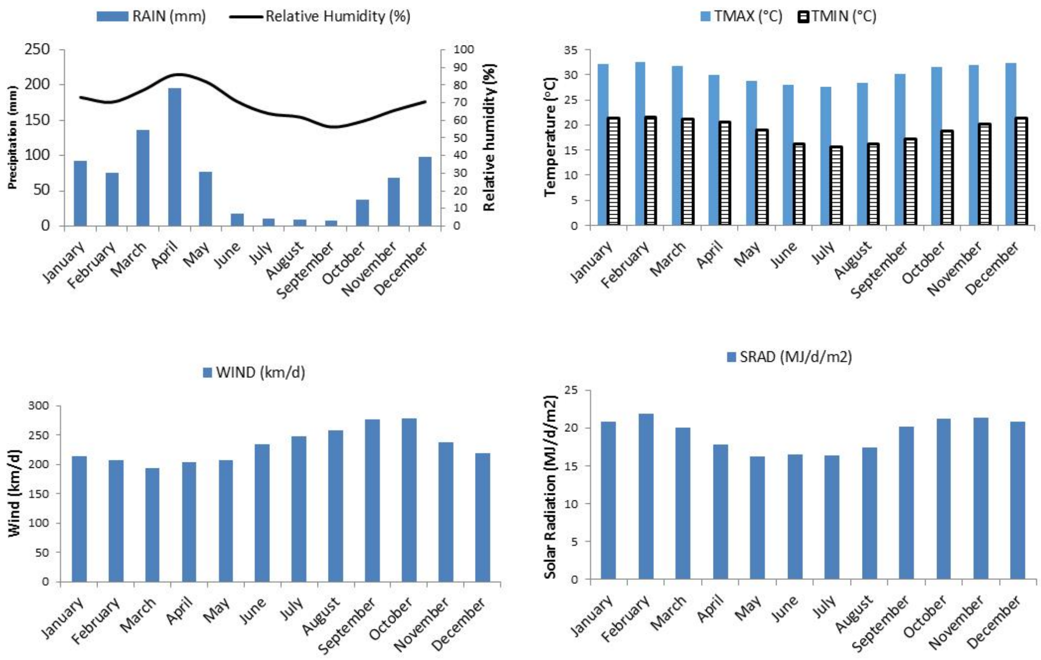


Figure 2: Mean monthly weather of Morogoro Tanzania (average of 1980 – 2010)

2.2. Experimental design

The experiments were conducted during Vuli periods in 2009/2010 season. The experimental field was divided into 12 sub-plots. A completely randomized design was used to test four supplemental deficit irrigation (DSI) levels with each level replicated three times (Figure 3). The treatments were based on the pre-determined irrigation water requirements (IWR), based on potential crop evapotranspiration calculated by the CROPWAT model (Smith, 1992), which was also used for irrigation scheduling at five days fixed interval and 90% irrigation efficiency throughout the cropping season. The model uses Penman–Monteith equation in its calculations, which is the adopted FAO standard equation (Allen et al., 1998) (Eqn. 1).

The Penman-Monteith form of the combination equation is:

$$\lambda ET = \frac{\Delta(Rn - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \quad (1)$$

Where λ ET is the latent heat flux, Rn is the net radiation, G is the soil heat flux, $(e_s - e_a)$ *represents the vapour pressure deficit of the air,* ρ_a *is the mean air density at constant pressure,* c_p *is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and* r_s *and* r_a *are the (bulk) surface and aerodynamic resistances.*

Gross IWR calculation was first done without considering rainfall, and then, the DSI's were deduced by subtracting average rainfall extracted from the long term seasonal averages. However, the actual supplemental IWRs were adjusted at site during applications by subtracting the rainfall recorded by an automatic weather station installed at site from the subsequently scheduled irrigation event. The irrigation levels / treatments were 60% (T1), 40% (T2), 20% (T3), and 0 % (T4) deficits application of actual IWR (Fig. 3).

Diviner 2000 access tubes were installed in each experimental plot for volumetric soil water content measurements and monitoring soil moisture fluctuations. The Diviner 2000 is a portable capacitance probe system allowing frequent measurements of soil moisture content deep in the soil through access tubes (Heng et al., 2002). Drip irrigation systems were installed following the layout of the experiment (Fig. 3). Emitters were spaced at 30 cm, which was also plant spacing; flow rate per emitter was 2.2 liters her hour and the lines were aligned in rows at 75 cm apart reflecting the row spacing. Flow control valves and meters were installed in every sub-main line for regulating the amount of water flowing into the field lines and measuring the amount of water released respectively. Uniformity of water droplets from drip system were monitored by putting water collecting cans at three spatial positions in each treatment plot; at the head, the middle and the tail diagonally across each plot. The coefficient of uniformity was excellent (>90%). Using flow meter we recorded the total amount of water supplied to each plot as per irrigation schedule.

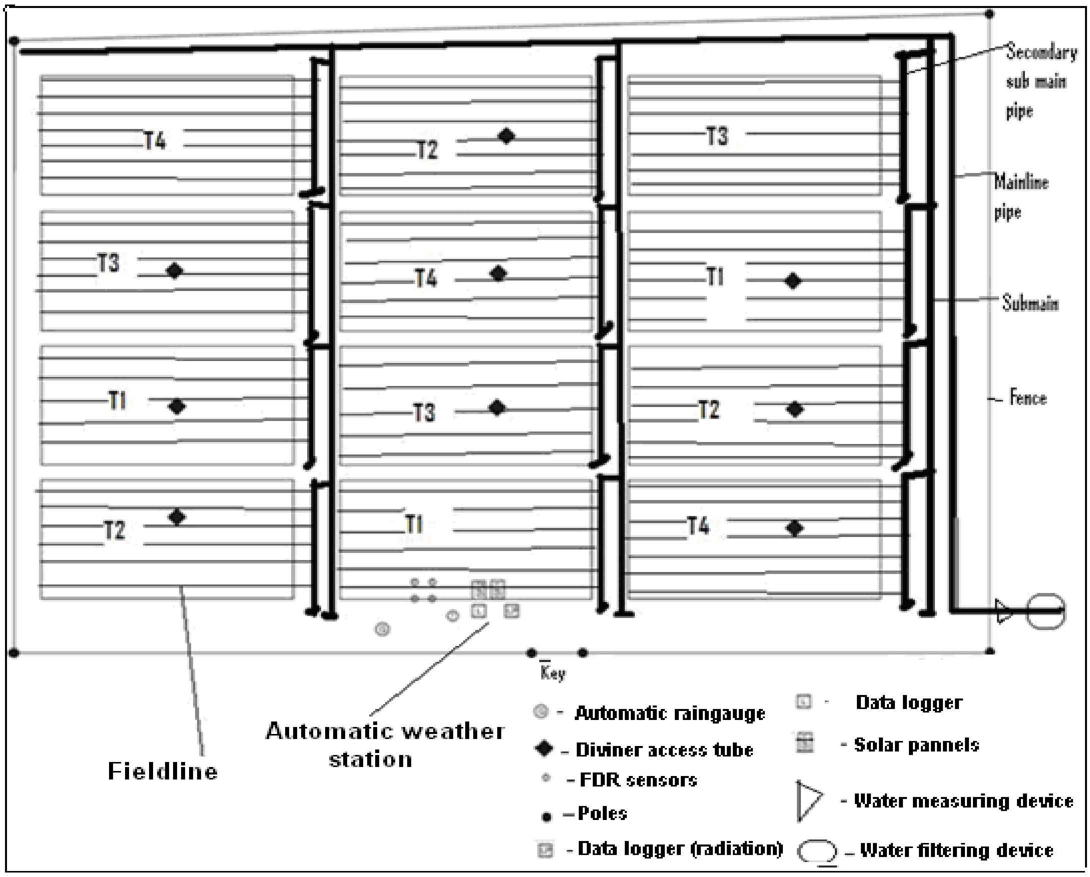


Figure 3: Sketch of the experimental set up at SUA Morogoro

2.3. Soil and crop data collection

Soil samples were collected for characterization of soil samples in order to determine its physical and chemical properties (Table 1 and 2). Classified as Ultic Haplustalfs, according to the USDA soil taxonomy, the soils were characterized by unconsolidated materials of metasediments, mainly consisting of hornblende pyroxene granulites, with plagioclase and quartz-rich materials. Improved maize variety TMV-1 (Fig. 4), released in 1987 by the Ilonga Agricultural Research Institute, was used for experiment. The variety is popular with many farmers in the mid-altitude and lowland zones. It has a white, flinty grain, is streak virus resistant, and has intermediate maturity (about 100-115 days). Maize was sown in late October and harvested in early February. The amount of fertilizer used for all treatments was 132 kg/ha Urea, equivalent to 61 kg/ha nitrogen. We measured biomass 45 days after planting (DAP), 75 DAP, and 105 DAP (at harvest), and grain yield.

Figure 4: Maize under drip irrigation at SUA Site Morogoro, Tanzania

Table 1: Physical soil characteristics and organic carbon and nitrogen content at SUA, Morogoro, Tanzania

	lower limit	drained upper limit	saturation	bulk density	organic carbon	organic nitrogen
Depth (cm)	LL % v/v	DUL % v/v	SAT % v/v	BD (g/cm3)	OC (%)	ON (%)
0-35	0.31	0.5	0.55	1.2	1.65	0.09
35-60	0.29	0.45	0.51	1.3	1.06	0.06
60-105	0.38	0.54	0.55	1.2	1	0.06
105-135	0.38	0.54	0.55	1.2	0.74	0
135-200	0.38	0.54	0.55	1.2	0.33	0

Table 2: Soil parameters at the trial site at SUA, Morogoro, Tanzania

Horizon	Ap	Bt1	Bt2	Bt3	Bt4	Bt5
Depth (cm)	0-30	30-55	55-77	77-100	100-130	130-190+
Clay %	47	61	61	67	71	69
Silt %	9	9	11	9	9	7
Sand %	46	30	28	24	20	24
pH H_2O	5.6	5.2	5.5	5.6	5.3	5.2
pH KCl	4.8	4.3	4.3	4.3	4.2	3.9
EC ms/cm	0.06	0.05	0.05	0.05	0.04	0.04
Mncmol(+)/kg	125	67	70.5	42	19.5	14.5
Fe cmol(+)/kg	41	15.7	20.3	13.2	5.7	2.9
Organic C %	1.4	0.9	0.8	0.7	0.7	0.6
Avail. P mg/kg Bray	5.7	4.3	4.8	4.9	9.5	4
SO_4-S	6.9	27.3	29.3	25.7	25.7	9
CEC cmol(+)/kg	16.6	17.4	16.6	17.6	16.2	17
Exch. Ca cmol(+)/kg	4.3	3.8	2.8	2.2	1.7	1.1
Exch. Mg cmol(+)/kg	3	3.4	4.2	4.9	4.6	2.9
Exch. K cmol(+)/kg	0.6	0.1	0.1	0.1	0.1	0
Exch. Na cmol(+)/kg	0.3	0.3	0.3	0.4	0.4	0.6

2.4. Irrigation, water productivity calculations, and data extrapolation

The potential crop evapotranspiration (CWR) (mm) from the CROPWAT model was converted to volumetric (m^3) IWR values using equation 2. Adjustments to irrigation amounts were made during the growth period by subtracting rainfall amounts recorded using the automatic weather station at the experimental site from a subsequent irrigation event. A zero or negative value or IWR represented no irrigation required on that day.

$$\mathrm{IWR} = \frac{(\mathrm{ETc} \times \mathrm{Kr} - \mathrm{R} + \mathrm{Lr}) \times \mathrm{A}}{1000} \quad (2)\ .$$

Where IWR is irrigation water requirements (m^3), ETc (mm) is Crop evapotranspiration, Kr is ground cover correction factor (Kr = 0.7)(Vermeiren and Jobling, 1980), R is effective rainfall amount (mm) as dependable rain (FAO/AGLW formula) recorded before the successive irrigation event, Lr is leaching requirement (Lr=0), and A is a plot area (m^2).

Water productivity (kg/m^3) is calculated as a ratio of yield (biomass or grain) to the amount of water supplied to the field (IWR) as recorded by a flow meter after releasing the volumetric irrigation water requirement (Eqn. 3). As it accounts for consumed and non-consumed fractions, this method of calculating WP is also backed by (Perry, 2011).

$$\mathrm{WP} = \frac{\mathrm{Y}}{\mathrm{TIWR}} \quad (3)$$

Where WP is water productivity, Y is yield (biomass or grain), and TIWR is the amount of water supplied to the field as recorded by water meter taking into account the possible losses.

The extrapolation of results is done by calculating the deficit-optimum ratio (DOR) (Eqn. 4) and extrapolated yields (EY) (Eqn. 5) as below:

$$\mathrm{DOR} = \frac{\mathrm{WP}_{\mathrm{i,j}}}{\mathrm{WP}_{\mathrm{i,o}}} \quad (4)$$

Where DOR is the deficit optimum ratio, $\mathrm{WP}_{\mathrm{i,j}}$ is water productivity at the i^{th} growth stage and j^{th} treatment, and $\mathrm{WP}_{\mathrm{i,o}}$ is water productivity at i^{th} growth stage and full supplemental irrigation (in this study, it is T4).

$$EY = DOR_{i,j} \times Y_{i,j} \quad (5)$$

Where EY is extrapolated yield ($tDWha^{-1}$), $\mathrm{DOR}_{\mathrm{i,j}}$ is the deficit to optimum ratio at i^{th} growth stage and j^{th} treatment, while $Y_{i,j}$ is the corresponding yield at i^{th} growth stage and j^{th} treatment.

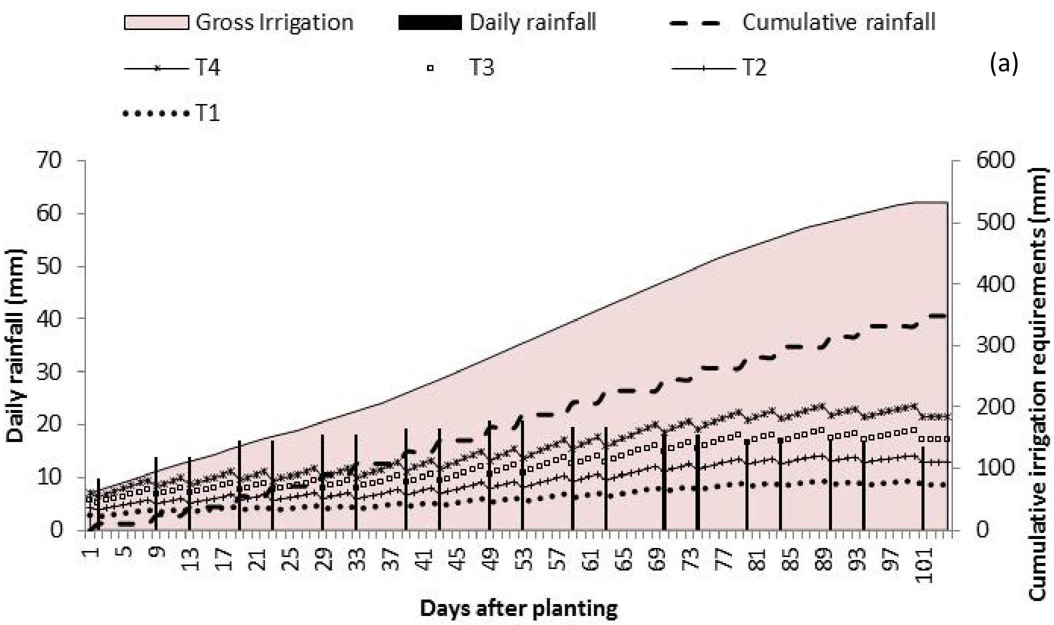
2.5. Statistical analysis

Scatter plots and response surfaces are used for interpreting rainfall, irrigation water levels, and soil moisture dynamics from diviner readings. ANOVA is used for analyzing biomass, yields, and WP values for inter-treatment variations. In case of significant differences (rejection of the null hypothesis) at 0.05 probability level, Tukey Kramer multiple comparison test was used to find the smallest significant between pairs of means from two individual groups.

3. **Results**

3.1. Crop water requirement under supplemental deficit irrigation

The gross crop water requirement for maize during vuli season is determined to be 532.3mm (T4); therefore, 425.84mm, 319.38mm, 212.92mm were the deficit application requirements for T3, T2, and T1, respectively, in case of no rainfall. However, the area receives an average rainfall of 347.6mm during the vuli cropping season. Thus, the supplemental pre-calculated irrigation water requirements (IWR) were 184.7mm, 147.8mm, 110.8mm, and 73.9mm for T4, T3, T2, and T1, respectively (Fig. 5). Since the actual seasonal rainfall recorded during the cropping seasons was 199.1mm, the actual supplemental irrigation water requirements adjusted at the site were 333.2mm for T4 representing a full supplemental irrigation (SFI), along with 266.6mm, 199.9mm, and 132.3mm for T3, T2, and T1, respectively representing supplemental deficit irrigation requirements (DSI) (Fig. 5). As expected, short rains were not enough to supply the required water for the maize crop. Therefore, strategic supplemental irrigation is important during this time to support maize growth and improve yields.



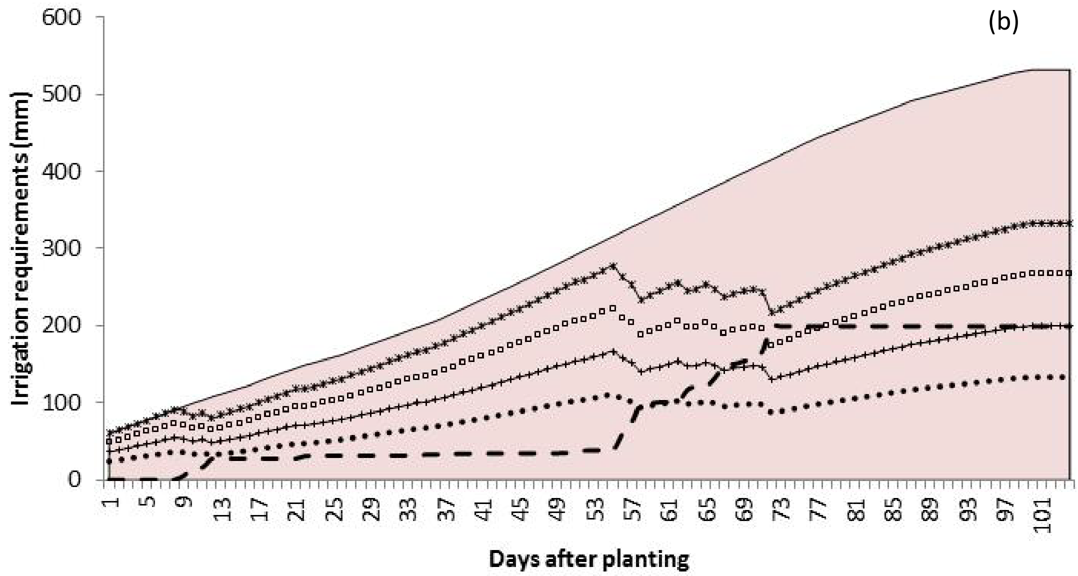


Figure 5: (a) Gross, pre-calculated irrigation water requirements; and (b) actual irrigation water requirements during the vuli season at SUA

3.2. Soil moisture patterns under different supplemental irrigation

Readings from diviner2000 show that the soil moisture pattern reflected the supplemental levels of irrigation, with T4 having highest soil moisture, followed by T3, T2, and T1. The replications (a, b, and c) were mostly within the acceptable range (more than 90% uniformity) due to the heterogeneity of soils.

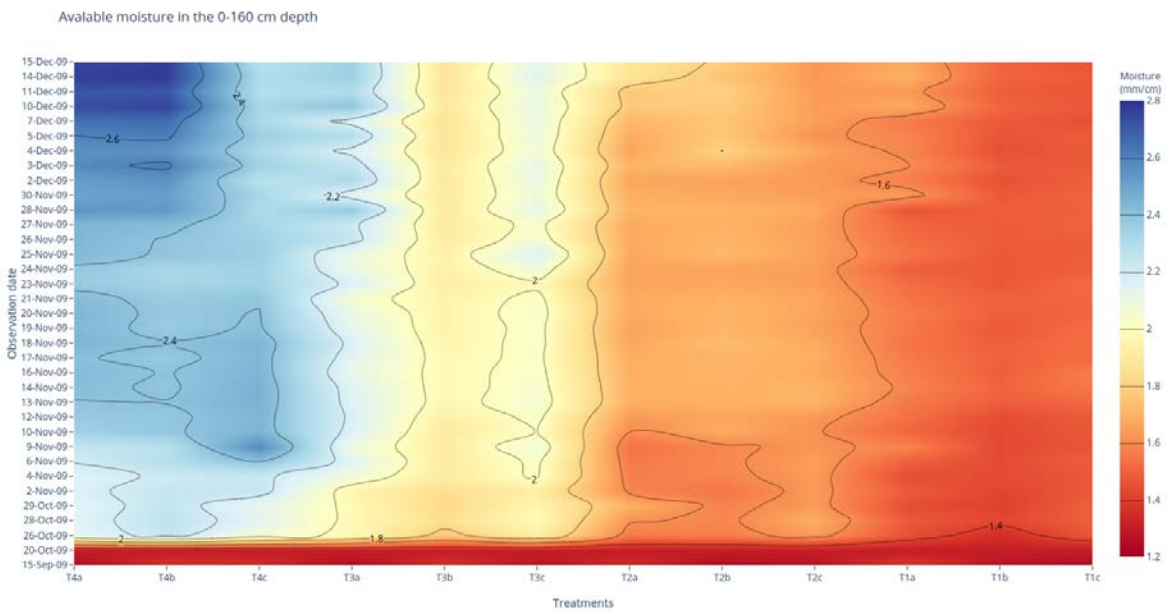


Figure 6: Response surfaces showing daily soil moisture balance (mm/cm) under different supplemental irrigation as recorded by the Diviner2000 soil moisture sensor.

This shows that the instrument is reliable in monitoring irrigation practices and soil moisture. Highly uniform values of soil moisture within replication were recorded under T2 and T1 (Fig. 6). This is explained by the fact that small applications of irrigation water crosses small depth across the soil profile, which is likely to be uniform in terms of textural characteristics.

3.3. Effects of supplemental deficit irrigation levels on maize biomass and yield

Biomass and grain yields in all treatments increased with increasing irrigation water application (Table 3). At 45DAP, mean biomass for 2.56, 3.02, and 4.06 $tDWha^{-1}$ for T1, T2, and T3, respectively (Fig. 7), were not significantly different ($p<0.05$). The rainfall recorded during this early growth stage was in excess as compared to DSI's that were required to be induced. Fig. 6 shows that the soil moisture under these treatments was similar, especially for T1 and T2. Similarly, mean biomass in T3 and T4 (6.26 $tDWha^{-1}$) were also not significant different. At 75DAP, mean biomass 6.64, 7.61, 8.34 $tDWha^{-1}$ for T1, T2, and T3, respectively, were also not significantly different, while mean biomass in T4 (10.72 $tDWha^{-1}$) was different compared to the rest of the treatment. Thus, the vuli short rains that were recorded during experiments were able to overcome the water deficits demands for T1,T2, and T3 at 75DAP stage; however, it was not able to cover the overall crop water demand in T4 (Fig. 7). At harvest (105DAP), mean biomass yield at T1 and T2 were not statistically different, similar to mean biomass of T3 and T4 (Fig.7), which provides an opportunity for water savings in biomass production. For grain yields, T4 produced highest mean grain yield across all treatments. Mean grain yields from T3 and T2 were not statistically different, similar to comparison of mean yields between T2 and T1 (Fig. 7).

Table 3: Biomass ($tDWha^{-1}$) at different growth stages and grain yields for different treatments

Growth stage	Replication	T1($tDWha^{-1}$)	T2($tDWha^{-1}$)	T3($tDWha^{-1}$)	T4($tDWha^{-1}$)
45DAPB	R1	1.90	2.43	4.07	6.25
	R2	2.20	2.80	4.23	5.03
	R3	3.58	3.83	5.49	7.44
75DAPB	R1	6.68	6.99	7.89	10.70
	R2	6.53	8.76	7.19	10.67
	R3	6.73	7.07	9.94	10.77
105DAPB	R1	10.95	9.92	13.62	14.27
	R2	9.47	10.66	12.49	13.32
	R3	10.06	8.14	12.88	13.76
Grain	R1	2.55	3.76	3.87	4.57
	R2	2.66	3.64	3.80	4.91
	R3	2.80	3.47	4.00	4.63

DAPB refers to days after planting biomass weight, tDWha^{-1} - refers to tons dry weight per ha

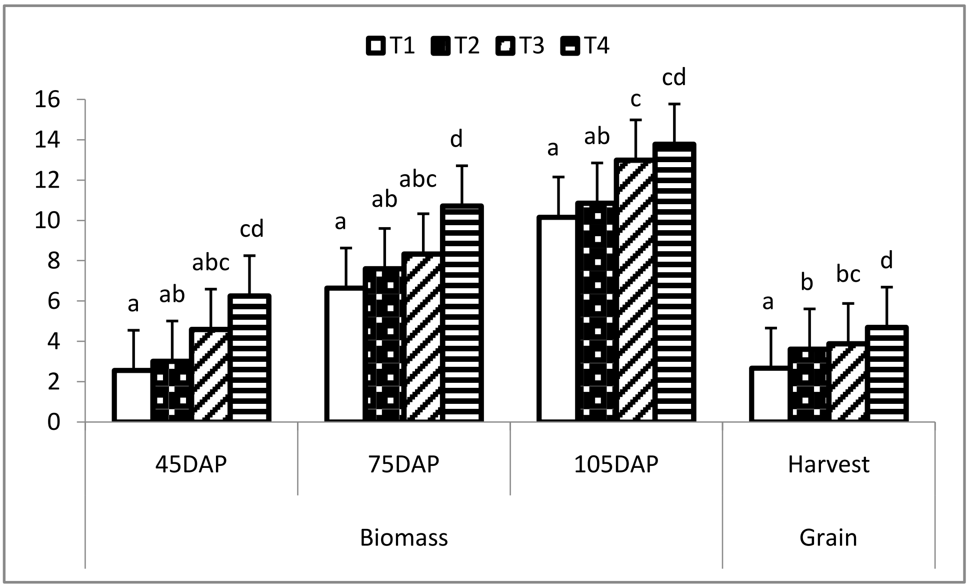


Figure 7: Average biomass and grain yield values at different growth stages and for different treatment (Means followed by same letters in the same column were not significantly different according to Tukey's Test at P≤0.05)

3.4. Effects of supplemental deficit irrigation on WP of maize biomass and grain

The values of WP decrease with increasing water supply at most of the growth stages (Table 4). Except for the 45DAP growth stage, mean WP values for biomass and grain of T1 were statistically different (p<0.05) from the rest of the treatments (Fig.8).

Table 4: Biomass and grain water productivity (kgm^{-3}) at different growth stages and treatments

Growth stage	Replication	T1*(kgm^{-3})*	T2*(kgm^{-3})*	T3*(kgm^{-3})*	T4*(kgm^{-3})*
45DAPBWP	R1	2.14	1.82	2.29	2.81
	R2	2.48	2.10	2.38	2.27
	R3	4.03	2.87	3.09	3.35
75DAPBWP	R1	7.13	4.97	4.21	4.57
	R2	6.97	6.24	3.84	4.56
	R3	7.19	5.03	5.31	4.60
105DAPBWP	R1	8.22	4.96	5.11	4.28
	R2	7.11	5.33	4.69	4.00
	R3	7.55	4.07	4.83	4.13
Grain WP	R1	1.91	1.88	1.45	1.37
	R2	1.99	1.82	1.43	1.47

R3	2.10	1.73	1.50	1.39

DAPBWP refers to days after planting biomass water productivity (kgm^{-3}).

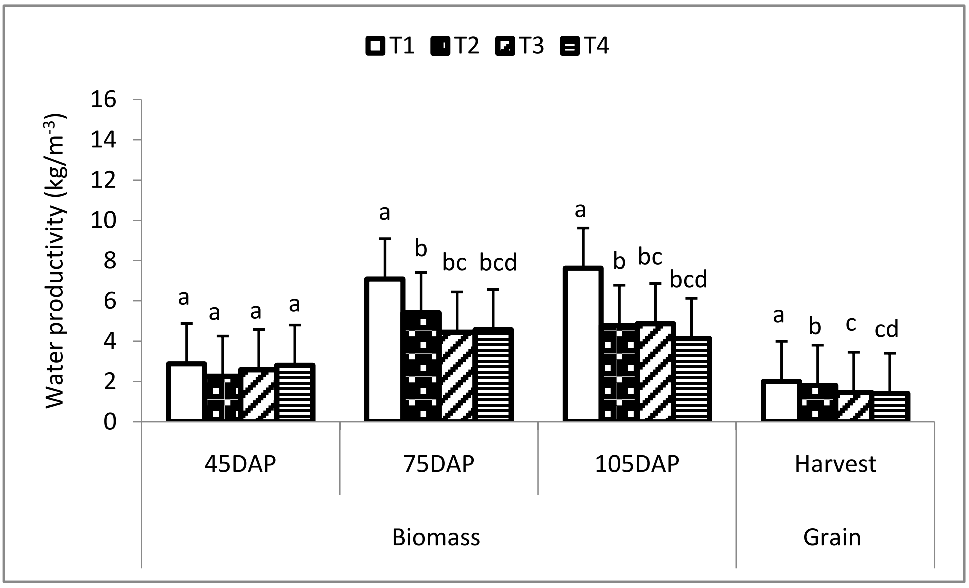


Figure 8: Average biomass and grain yield values at different growth stages and for different treatment (Means followed by same letters in the same column were not significantly different according to Tukey's Test at P≤0.05)

Other values of mean biomass WP for T2, T3, and T4 were not different at all stages, similar to grain WP for T3 and T4 (Fig. 8). During the initial growth stages (45DAP), it was advantageous to provide 20% deficits of supplemental irrigation requirements (T3). This was partly explained from the non-significant water productivity values (Fig. 8) for all treatments at 45DAP, while offering the balance of plant growth, as biomass under T3 was not different to the rest of the treatments. Despite the lowest yields in T1, this application produced significantly higher mean biomass water productivity at the 75DAP and 105 DAP growth stages, meaning that it was the most successful management option for supplemental irrigation in terms of water use efficiency at these growth stages. On the other hand, WP values for T2, T3, and T4 were not significantly different for growth stages 75DAP and 105 DAP, implying that there were no comparable advantages between supplying FSI and DSI. Except for T3 and T4, mean grain WP were significantly different. Similarly, T1 produced the highest mean grain WP (2 kg.m^{-3}), followed by T2 (1.81 kg.m^{-3}), T3 (1.46 kg.m^{-3}), and T4 (1.41 kg.m^{-3}) (Fig. 8).

3.5. Deficit-optimum ratio and extrapolated yields

The deficit-optimum ratio was as expectedly high under T1, followed by T2, T3, and T4 (Table 5). This implies that, with a unit of water available, extra yield was found under DSI level T1 than the rest at all stages. At harvest, T1 and T3 produced more biomass than T4 and T2 for every unit of water. However, grain yield were still high under T4 (4.70 $tDWha^{-1}$) than the rest of the treatments (Table 5).

Table 5: Deficit-optimum ratio and extrapolated yields at different growth stages and treatments

Deficit-optimum ratio				Extrapolated yields ($tDWha^{-1}$)			
T1	T2	T3	T4	T1	T2	T3	T4
1.03	0.81	0.92	1.00	2.63	2.43	4.23	6.26
1.55	1.18	0.97	1.00	10.30	9.00	8.11	10.72
1.84	1.16	1.18	1.00	18.73	12.57	15.31	13.78
1.42	1.28	1.03	1.00	3.79	4.65	4.02	4.70

Deficit-optimum ratio (DOR) is the ratio of water productivity at any growth stage under given supplemental deficit irrigation to the water productivity of full supplemental irrigation (T4) at that stage. The extrapolated yield is the product of DOR at any stage under given supplemental deficit irrigation with the yield of that stage under supplemental irrigation level.

4. Discussion

Generally, supplying less irrigation water requirement causes stress to the crop, negatively affecting both biomass and grain yields (Igbadun et al., 2008; Pandey et al., 2000). However, many studies show that the practice can help improve water use efficiency and expand irrigated area (Pandey et al., 2000). The level of induced deficits for different crops are subject to a wider discussion, with other studies finding that, for maize, when the deficit level is more than 50%, it may retard plant growth, resulting in a total production loss (Greaves and Wang, 2017; Trout and DeJonge, 2017). This study considers DSI, implying that rainfall primarily provides the crop water requirements, with irrigation supplementing shortages from rainfall. Thus, the tested levels of 60% deficits, which is slightly higher than the 50% limit (Greaves and Wang, 2017; Trout and DeJonge, 2017), along with 40, 20, and 0% deficits provided an understanding of DSI and its advantages in terms of water use efficiency and yields.

DSI is not advantageous during initial growth stages (45 DAP), as, at this level, maize should be provided with at least 80% of the FSI requirements (T3) since it provides the best balance of growth and water productivity values. However, FSI (T4) at 75DAP also results in the highest biomass values; it is during this stage of flowering that maize crops require sufficient water supplies for grain formation and grain filling, which is a critical stage. Since growth stages at 45DAP and 75 DAP did not produce a significant difference in WP for T2, T3, and T4, crop growth at these stages was an important factor in deciding upon the DSI level. Still, we record sound yields under the highest stressed treatment (T1), in agreement to Trout et al. (2010), who reported that 270 mm of ETc is required to produce the first unit of maize grain yield.

Treatments are also gauged against the achievable production per unit volume of water and possible yields. In this regard, T1 results in higher values of deficit-optimum ratio than all other treatments. This implies that, under T1, the production per unit of water is the highest, the target that is recommended by many findings (Fereres and Soriano, 2006; Howell, 2001; Pandey et al., 2000). Thus, T1 is the best option level if the goal is to produce large volumes of biomass per unit of water of DSI. Conversely, for grain yields, T4 was the best option, despite generally having lower WP, as the water saved in other treatments did not compensate for the grain yield differences between DSI levels and FSI (T4). These contradicting advantages can be harmonized by choosing to induce DSI to save water and improve WP during certain less sensitive growth stages, as suggested by Chai et al., (2016).

The study presents design, instrumentation, and high data resolutions that are unique. Although such experiments are rare, these can enlarge the availability of quality data for future modeling studies. Although, the limitation of data collection to one season is a weakness, we assume that our results could apply to any short rainy season in SSA.

5. Conclusions

In our study, we find that maize crops still grow adequately when the water requirement is slightly reduced. During short seasonal rainfall, providing supplemental irrigation is among practices that improve yields and water use efficiency, thus increasing food production. Improving water productivity helps to produce more crops with available water. Instead of waiting for long rain seasons, which are currently very erratic, it is advised to consider supplementing rainfall with irrigation, thus compensating for fluctuations and shortages of water. This option also addresses the challenge of unpredictable rainfall, either unimodal or bimodal, in other SSA regions. The decision to apply deficit irrigation relies on the production aims, land availability, and the level of understanding of the farmers to take advantages of the conflicting advantages of DSI and FSI. If the aim is to produce more maize biomass, then DSI is the best option. However, if the aim is to improve grain yields, then FSI is the best option. Synergies of the two can be identified through further experiments or modeling the growth stages by inducing water stress to the crop during less sensitive growth stages.

Acknowledgments: The paper is part of the ReACCT project, which received funding from the German Federal Ministry for Economic Cooperation and Development (BMZ). The publication of this article is funded by ZALF, Germany.

Conflicts of Interest: The authors declare no conflict of interest. The views expressed are purely those of the authors and should not under any circumstances be regarded otherwise.

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