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The Effects of Water Regimes on Growth, Yield Attributes and Water Productivity of Wheat in Tropical High Terrace Soil, Sudan

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Abstract

Purpose

The purpose of this study is to examine the effects of different water regimes on growth, yield attributes and water productivity of wheat production in the tropical high terrace soil of northern Sudan.

Design/methodology/approach

An analysis of variance and economic analysis were used to compare treatment means and estimate net financial return.

Findings

Our findings discovered
(i) the increase in grain yield at high irrigation levels I_5 and I_4 compared to low irrigation treatment I_1 was about 48% and 42%, respectively;
(ii) crop water productivity increased significantly with the amount of water applied;
(iii) net financial return increased significantly with irrigation increases until the optimal level of capacity was reached.

Originality/value

The approach and the resulting framework are original and valuable in measuring the effects of water regimes on growth, yield and water productivity of wheat.

Keywords

water regimes, water productivity, grain yield, wheat

Introduction

Wheat (*Triticum aestivum* L.) production is one of the most important cereal crops in Sudan. The success in wheat research has enhanced the expansion of the wheat area; the intensification and diversification of cropping systems has increased the land available for wheat production. The total cultivated area in 2018/19 was estimated to be 235,000 hectares, compared to 173,000 hectares the previous year. The five year average of cultivated land was 218,000 hectares (FAO, 2019). Wheat is grown under irrigation during the short dry and comparatively cool winter season that extends from November to March. The short hot dry season and inadequate irrigation water are the major factors responsible for the commonly low yields. Wheat consumption in Sudan, particularly in the rapidly growing urban areas, has been rapidly increasing.

River Nile State is considered to be the best area for the production of temperate crops, especially cereals, broad beans and other winter crops. The area has three advantages: first, the availability of water throughout the year from the River Nile, Atbara River and the great reserve of underground water; second, the climate is suitable for growing different crops, mainly winter crops; and third, the farmers in the State are very skilled and efficient. Despite all the above-mentioned conditions and advantages, the yields of most crops grown in the state are very low.

The world's population is expected to increase from the current 7.7 billion to 9.7 billion by 2050 (UN, 2020); therefore, it will be essential to increase food production. In most regions of the world, over 70% of fresh water is used for agriculture. By 2050, feeding a planet of 9 billion people will require an estimated 50% increase in agricultural production, and a 15% increase in water withdrawals (World Bank, 2020).

Therefore, sustainable methods of increasing crop water productivity are gaining importance in arid and semi-arid regions. Water productivity with dimensions of kg m^{-3} is defined as the ratio of the mass of marketable yield to the volume of water consumed by the crop evapotranspiration, as suggested by Geerts and

Raes (2009). An increase in water productivity could lead to greater agricultural production, and more benefits could be obtained with fewer water resources. Increasing water productivity is an important way of alleviating water stresses and ensuring agriculture production.

Wheat is an important cereal crop around the globe. According to Fahad et al. (2017), nearly 50% of the area under wheat cultivation is subject to periodic drough. The wheat grain yield is a result of the contribution of many traits, including plant height, length of spike, and number of spikelets per spike (Zečević et al., 2004; Walsh et al., 2020).

Water use efficiency (WUE) is the grain yield produced by crop consumption per unit of water consumption. It is a comprehensive physiological indicator for assessing the appropriateness of crop growth and water use (Zhao et al., 2020).

The application of water below the evapotranspiration requirements is termed deficit irrigation: water deficit plays a very important role in inhibiting the yields of crops. Deficit irrigation would be an effective irrigation practice to reduce irrigation water and increase WUE, because plants can reduce their leaf transpiration and soil evaporation to minimise water consumption (Blum, 2009; Farooq et al., 2019). However, with increasing water scarcity in dry areas, full supplemental irrigation should be replaced with a level of deficit irrigation that should be determined by water availability and the specific crop response (Karrou and Oweis, 2012).

To cope with scarce supplies, the deficit irrigation technique, defined as the application of water below full crop-water requirements in order to improve WUE, should be used (Geerts and Raes, 2009; Galindo et al., 2018).

Water is an essential resource for food production and is considered as an input highly effective in increasing agricultural products. Water shortage is becoming critical in arid and semi-arid areas worldwide; therefore, it is vital to use water efficiently (Abdelkhalik et al., 2019).

The applied WUE describes how efficiently water is used for plant biomass production and

is therefore highly relevant for water-limited agricultural systems (Stallmann et al., 2020).

Koech and Langat (2018) defined WUE in two ways, volumetric or hydrological approach; this is the amount of water supplied through irrigation that is productively used by the plant. Tilahun et al. (2011) mentioned an additional definition; the yield of marketable crop produced per unit of water used is known as evapotranspiration.

According to Gebremariam et al. (2018), the application of deficit irrigation up to 30% of crop evapotranspiration can save a significant amount of irrigation water, without substantial yield reduction. Deficit irrigation has been widely investigated as a valuable and sustainable production strategy in dry regions. By limiting water applications to drought-sensitive growth stages, this practice aims to maximise water productivity. Therefore, the water saved can be used to irrigate extra land and/or crops, and this leads to increased overall production (Oweis and Hachum, 2008). In this way, water demand for irrigation can be reduced and the water saved can be diverted for alternative uses.

Some research results indicate that deficit irrigation can increase water productivity (WP) for various crops without causing severe yield reductions (Ali et al., 2007; Geerts and Raes, 2009). Recently, emphasis has been placed on the concept of water productivity. Crop water productivity (CWP) is a measure for the performance of irrigation systems and describes the efficiency of the physical system and operational decisions that deliver water from a water source (Irmak et al., 2011). WP is used to define the relationship between crop produced and the amount of water involved in crop production, expressed as crop production per unit volume of water (Kadaja and Saue, 2016). WP increases under deficit irrigation, relative to its value under full irrigation, as shown experimentally for many crops (Zwart and Bastiaansen, 2004; Fereres and Soriano, 2007).

In recent years, some researchers found that good management and the adoption of appropriate practices could improve agricultural water use, and crop production would be more efficient (Iglesias and Garrote, 2015; Dai, 2020).

At present, most research is focused on how to maintain the best economic productivity and highest WUE in arid and semi-arid areas (Yagoub et al., 2012; Sánchez et al., 2015; de Oliveira Feitose et al., 2016; Wakchaure et al., 2016).

Deficit irrigation has not received sufficient attention in applied research. There is a potential approach for improving WP in many field crops, and there is sufficient information for defining the best deficit irrigation strategy for many situations. Therefore, the objective of this study is to examine the effects of different water regimes on growth and yield attributes, and water productivity of wheat production in tropical high terrace soil in northern Sudan.

Materials and Methods

The field experiment was conducted during the 2012/2013 and 2013/2014 seasons at the Experimental Farm of the Faculty of Agriculture, Nile Valley University, Darmali, Sudan (17°48' N; 34°00' E; altitude 346.5 metres above sea level). The physical and chemical properties of the soil in the experimental site were obtained from samples analysed in the Hudeiba Research Station Laboratory; these are presented in Table 1.

The climate data were obtained from Atbara meteorological station. They included mean maximum and mean minimum temperatures, mean relative humidity, mean sunshine, and wind speed. Monthly means are presented in Table 2.

Table 1: Some physical and chemical properties of soil in the experimental site

Soil properties	Value
Calcium Carbonate	15%
Organic matter	0.042%
Nitrogen	140PPM
Phosphorus	1.1PPM
EST	1.2%
Electric conductivity	0.85 d/m
Soil texture	Sand 35%, Clay 63%, Silt 2%
P^H	7.4

Source: Soil samples analysed in Hudeiba Research Station Laboratory, 2012

Table 2: Monthly mean maximum temperatures (ºC), relative humidity (%) and pan evaporation during both seasons

Season	Month	Air temperature in ºC				Relative humidity %	Wind Mean Speed at 2m MPD
		Maximum		Minimum			
		MEAN	HST	MEAN	LST	MEAN	
2012/2013	NOV	34	40	23	16	22.7	12
	DEC	29	35	18	13	26.3	11
	JAN	37	31	20	13	29.0	11
	FEB	39	31	21	11	24.4	12
	MAR	44	36	24	16	16.5	12
2013/2014	NOV	35	40	26	21	28.2	11
	DEC	29	36	20	13	32.0	13
	JAN	25	34	16	10	32.6	14
	FEB	30	38	21	13	20.0	16
	MAR	32	41	23	16	18.0	16

* Calculated by using Penman-Monteith equation

Source: Sudan Meteorological Authority, Atbara Station.

The calculation of reference evapotranspiration (ET_o) is based on the FAO Penman-Monteith method (Allen et al., 1998). Irrigations were added at seven day intervals. Before starting the experiment, plants were irrigated to the plot capacity for two weeks in order to improve root development.

The experiment consisted of five irrigation levels (0.40 ET "I_1", 0.55 ET "I_2", 0.70 ET "I_3", 0.85 ET "I_4" and 1.00 ET "I_5"); these were replicated three times in a randomised block design. The irrigation application to each plot was measured using a flowmeter that was installed at the hydrant of a low-pressure tube water transportation system.

The land was prepared by disc plough and disc harrow then each plot was levelled manually. Each treatment plot had dimensions of 0.8m x 1.6m. Plots in each replication were separated by a 3m wide buffer zone to eliminate runoff. The wheat cultivar (Imam) was sown on 15 November in both seasons at a seed rate of 120kg ha^{-1}. Planting was done manually by hand dibbling.

Triple super phosphate (48% P_2O_5) was applied as a source of phosphorous before sowing. Urea (46% N) was applied in split dose as a source of nitrogen, half-dose applied at sowing and the rest four weeks after sowing. The experiment was kept clean by hand-weeding two and three weeks after sowing.

For soil moisture content determination, the soil samples were taken before and after irrigation during the growing season. Locations were randomly selected within plots and samples were taken by auger from two soil depths, 0-15cm and 15-30cm. The samples were transferred to the laboratory using polyethylene bags. Samples were weighed wet and then left to dry in an oven. The soil moisture content on a dry basis was calculated as follows:

$$M\% = \frac{W_1 - W_2}{W_2 - W_3}$$

Where: W_1 = weight of bag with wet sample, W_2 = weight of bag with dry sample, W_3 = weight of empty bag, and M = moisture content %.

Plants were harvested as they dried up. Shoots were removed manually by cutting at the soil surface. Plants were harvested, bound and air dried before threshing and measuring seed yield per unit area.

Water productivity (WP) was calculated as follows:

$$WP = \frac{Y}{ET}$$

Where: Y is the grain yield (kg ha^{-1}), and ET is crop water use or evapotranspiration (cm).

Productivity of irrigation water (PIW) was calculated as:

$$PIW = \frac{Y}{I}$$

where I is the irrigation water applied (cm).

Relative water savings (RWS) were calculated as:

$$RWS = \frac{I_5 - I}{I_5} x100$$

Relative yield decrease (RYD) was calculated as:

$$RYD = \frac{Y_5 - Y}{Y_5} x100$$

As proposed by Ali et al. (2007), the marginal productivity of a particular resource is defined as the addition to the gross output caused by an addition of one unit of that resource while other inputs are held constant. Then, marginal productivity of irrigation water (MPIW) can calculated as follows:

$$MPIW = \frac{\Delta Y}{\Delta I}$$

Total operating cost ($/ha)

Total operating (variable) cost consisted of the cost of tillage (hiring of a power tiller), seed, fertiliser, irrigation, insecticide, and human labour. This was calculated as:

$$TVC = X_1 + X_2 + X_3 + X_4 + X_5 + X_6$$

Where TVC = total operating (variable) cost ($/ha), X_1 = cost of tillage ($/ha), X_2 = cost of seed ($/ha), X_3 = cost of fertiliser ($/ha), X_4 = cost of irrigation ($/ha), X_5 = cost of insecticide ($/ha), and X_6 = cost of labour ($/ha).

Gross return was calculated by multiplying the total amount of product by their respective market prices as follows:

$$GR = Y \,.\, P$$

Where Y = total amount of product, GR = Gross return ($) and P = respective market prices ($).

Net financial return was calculated by subtracting the total cost from the gross return:

$$NFR = GR - TC$$

Where NFR ($) = Net financial return ($) and TC = Total costs ($)

Data were observed on ten plants randomly selected from the harvest area. Parameters assessed included: plant height (soil surface to tip of growing point) and one-thousand grain weight (kg). Harvest index was calculated as the average grain yield per plot divided by the average dry biomass per plot (HI %). Seed yield per unit area was obtained from the three centre rows of each plot. To avoid a border effect, 0.5m of every side in each plot was not considered when harvesting. Grain yield was then achieved as kg ha^{-1}.

Data were analysed using an analysis of variance to test the significance of treatment effects. A Least Significant Difference Test was used to compare treatment means using the computer program SPSS.

Results and Discussion

Leaf area index

The maximum leaf area index was attained at higher irrigation levels. However, a reduction in the leaf area index was recorded at irrigation level treatments I_1 and I_2. This might be due to the fact that available soil water is less than root water extraction efficiency. During wheat vegetative growth, under water stress, leaves became smaller; this results in low leaf area index (Magsood et al., 2012). Several studies indicated that total resistance in the soil plant system increases with decreasing soil-water potential; this leads to reduced photosynthetic activity and growth (Ali et al., 2007; Ngwako and Mashiqa, 2013).

Plant height (cm)

Plant height was significantly affected by irrigation levels. The results indicated a decline in plant height as irrigation levels under moisture stress (Khakwani et al., 2011; Shirazi, 2014).

Spike length (cm)

The spike length was affected significantly by irrigation levels (Table 3). Irrigation level treatment I_5 gave the highest spike length. Similar results of minor decreases in spike length following irrigation levels deficit were obtained by Dalvandi et al. (2013).

1000-kernel weight (g)

One thousand kernel weight was significantly increased by irrigation levels (Table 3). The maximum 1000-kernel weight (35.2g) was found under I_2 irrigation treatment, and the lowest (30.4g) was found at I_1 irrigation treatment. The decrease in 1000-kernel weight may be due to disturbed nutrient uptake efficiency and photosynthetic translocation within the plant, which produced shrivelled grains due to hastened maturity (Bogale and Tesfaye, 2011).

Harvest index (%)

The harvest index was significantly affected by irrigation levels (Table 3). The highest harvest index (29.6%) was recorded at irrigation treatment I_4; this could be due to the maximum translocation of assimilates to grain formation. On the other hand, irrigation treatments I_1 and I_2 attained the lowest harvest index at 26.0% and 21.1%, respectively. The studies revealed that water stress at different growth stages of wheat significantly reduced total dry weight, grain yield, and harvest index. Dalvandi et al. (2013) reported similar findings, that drought stress had a significant effect on the harvest index.

Grain yield (kg ha^{-1})

The results revealed that grain yield response to irrigation varied considerably due to differences in soil water regimes, as shown in Table 3. The combined analysis over two growing seasons for the irrigation levels recorded a significant effect. Irrigation level treatments I_5 and I_4 gave significantly the highest grain yield, 2,784kg ha^{-1} and 2,338kg ha^{-1} , respectively. Whereas the lowest grain yield (1,856kg ha^{-1}) was recorded at irrigation treatment I_1. Consistently higher values of harvest index were obtained from the I_5 treatment. The harvest index decreased with decreasing irrigation water amount. It was evident that the average grain yield of treatment I_1 was lower than those of other treatments; this showed that severe soil water deficit markedly decreases grain yield of wheat compared with other treatments. This might be due to leaf area index, spike length, and harvest index. Grain yield was affected by both the magnitude of water deficit and storage of growth subjected to deficit. In the same way, Rizk and Sherif (2014) reported that the highest grain yield was recorded at available soil moisture of 80%, while the lowest values were obtained at 40% available soil moisture. The grain yield was lower for I_1 treatment; this could be due to the fact that soil moisture was depleted sufficiently enough to limit extraction of water by roots, and thereby water stress caused large deficiencies in grain yield. The results were similar to the findings of Yagoub et al. (2012), who noted rational irrigation significantly increased biomass and grain yield.

Table 3: Effect of irrigation levels on grain yield and yield components of wheat over two seasons (2012/2013 and 2013/2014)

Treatment	Grain yield (Kg /ha)	Spike length (cm)	1000-kernel weight (g)	Harvest index (%)	Plant height (cm)	Leaf area index
I_1	1856c	4.6b	33.5ab	26.0b	58.0c	1.40c
I_2	1919bc	5.6a	35.2a	21.1c	58.6c	1.50c
I_3	2280b	5.6a	34.7a	26.3b	60.4a	1.67bc
I_4	2338ab	5.4a	31.1bc	29.6a	59.5b	1.88ab
I_5	2784a	5.8a	30.4c	28.5ab	59,2bc	1.99a
LSD($P \geq 0.05$)	428.678	0.52	2.46	3.76	0.27	0.29

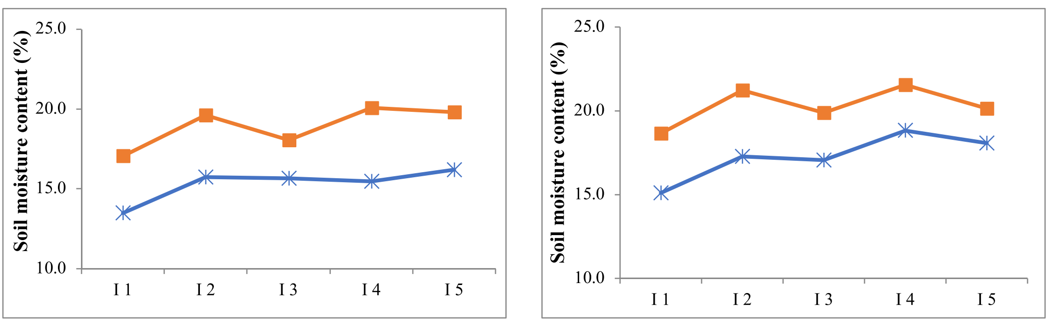
Least Significant Difference Test is significant at the 0.05 level (NS) not significant.

Source: Calculated by authors from field experiment data

Soil moisture content

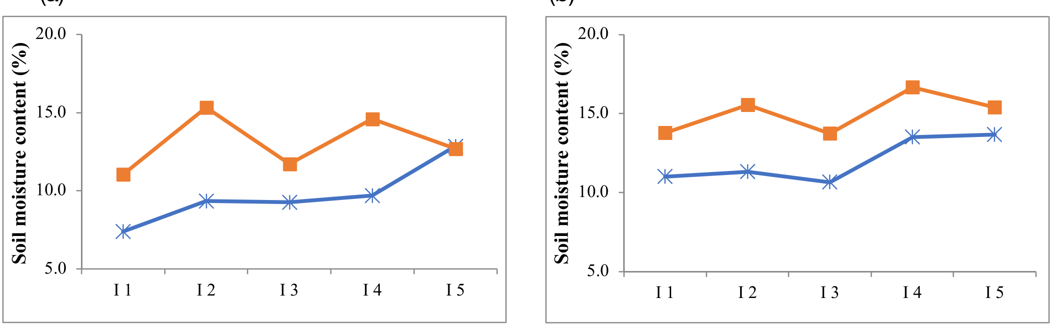
Soil moisture content was measured before and after irrigation during the growing seasons at a soil depth of 0-30cm (Figure 1). Soil moisture content at 30cm depth for I_4 was higher than those for I_1, I_2, and I_3 treatments. The I_4 and I_5 treatments had greater values than the others because of a greater amount of water per irrigation. This indicates that soil moisture content within the top 0-30cm of soil was available for growing. The greatest decrease in grain yield due to water deficits was 33% at lower irrigation rate I_1. These results are in agreement with those reported by El-Hendawy et al. (2008) and Mesbah (2009).

(a) (b)



Season 2012/2013

(a) (b)



Season 2013/2014

Figure 1: Soil moisture content before and after irrigation at depth 0-15cm (a) and 15-30cm (b) during season 2012/2013 and 2013/2014

Before irrigation After irrigation

Source: Soil samples analysed in Faculty of Agriculture Laboratory.

Water productivity

Water productivity (WP) and productivity of irrigation water (PIW) were influenced by irrigation levels (Table 4). The highest water productivity of irrigation was obtained under I_5, indicating that the irrigation was most efficiently used at this irrigation level. As any increase in yield compared to I_1 at some high level of yield, an incremental yield increase requires larger amounts of water. At the same time, productivity of irrigation water decreased as the grain yield increased. The results were similar to the findings of Ali et al. (2007). Irrigation level I_1 saved about 67% water compared to I_5 irrigation level, with a yield reduction of 33%. Productivity of irrigation water for I_4 irrigation level was similar to that of I_5. It only caused a reduction in grain yield of about 16%. Crop water productivity can be increased significantly when irrigation is applied (Oweis and Hachum, 2008; Tadayon et al., 2012).

Table 4: Water productivity (WP), productivity of irrigation water (PIW), relative water savings (RWS), relative yield decrease (RYD), and marginal productivity of irrigation water (MPIW), by treatment

Treatments	Yield Kg ha^{-1}	Irrigation Applied cm	WP Kg (ha cm)$^{-1}$	PIW Kg (ha cm)$^{-1}$	Increase in yield compared to I_1 %	RWS compared to I_5 %	RYD compared to I_5 %	MPIW kg (ha cm)$^{-1}$
I_1	1856	175.0	42.0	10.6	-	66.67	33.3	-
I_2	1919	272.2	43.4	7.0	3.4	48.15	31.1	0.6
I_3	2280	350.0	51.6	6.5	22.8	33.33	19.1	2.4
I_4	2338	447.2	52.9	5.2	26.0	14.81	16.0	1.8
I_5	2784	525.0	63.0	5.3	50.0	-	-	2.7

Source: Calculated by authors from field experiment data

Economic return

The optimum water application strategy will be that which maximises net return per unit of land. Total cost of production consisted of total operation cost and interest on operating capital. The operating capital consisted of the cost of tillage (hiring of a power tiller), seed, fertiliser, irrigation, insecticide, and human labour. Interest on operating capital was charged at the rate of 12% per annum. Gross return was calculated by multiplying the total amount of product by their respective market prices. Net financial return was calculated by subtracting the total cost from the gross return. Cost and revenue per hectare are presented in Table 5. These show that the maximum net financial return (US$316.6ha^{-1}) obtained under I_5 compared to other irrigation treatments I_1, I_2, I_3 and I_4. The results of economic analysis showed that net financial return can be increased significantly if irrigation increases until optimal level of capacity is reached (the law of diminishing marginal returns). The results will be helpful in policy planning regarding irrigation management for maximising net financial returns.

Table 5: Grain yield, price, revenue, total operating cost, interest on operating cost and net return under different irrigation level treatments of bread wheat cultivar

Treatment	Grain yield kg ha^{-1}	Price $ kg^{-1}	Revenue from wheat $ ha^{-1}	Total operating cost $ ha^{-1}	Interest on operating cost $ ha^{-1}	Total cost $ ha^{-1}	Net return $ ha^{-1}
I_1	1856	0.37	686.7	614.6	73.8	688.4	-1.6
I_2	1919	0.37	710.0	620.8	74.5	695.3	14.7
I_3	2280	0.37	843.6	625.8	75.1	700.9	142.7
I_4	2338	0.37	865.1	632.0	75.8	707.9	157.2
I_5	2784	0.37	1030.1	637.0	76.4	713.5	316.6

Note: '$' means US$; 1 US$ = 55 SDG

Source: Calculated by authors from field experiment data

Conclusions

The objective of this study was to examine the effects of different water regimes on growth, yield attributes and water productivity of wheat production in tropical high terrace soil in northern Sudan. The results of this study indicate that the increase in grain yield at high irrigation levels I_5 and I_4 compared to low irrigation treatment I_1 is about 48% and 42%, respectively. Crop water productivity increased significantly with the amount of water applied. The results of economic analysis showed that net financial return can be increased significantly if irrigation increases until optimal level of capacity is reached. This is important information for policymakers for formulating improved planning regarding irrigation management practices.

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