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Assessment of actual evapotranspiration and yield of wheat under different irrigation regimes with potassium application

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Abstract

Water shortage at precarious growth stages diminishes the wheat production, however regulated deficit irrigation and potassium fertilization ameliorate its adversities to a certain extent. A pot experiment was conducted in 2010-11 and 2011-12 growing seasons to assess the effect of regulated deficit irrigation on yield and water use efficiency of wheat under semiarid region of Pakistan. The growing season was divided into six periods viz: germination, jointing, booting, heading, grain filling and maturity stage. Three regulated deficit irrigation levels (no- soil- water- deficit (H: 80-100 % of available water content (AWC)), medium (M) soil water deficit (70 to 80% AWC and severe (L) water deficit (60-70% AWC) were maintained at above mentioned stages in combination with three levels of potassium (0, 200 and 300 kg ha^{-1} K_2O). Soil water contents were measured gravimetrically by weighing pots after 1 to 2 day's interval throughout the growing season. Potential evapotranspiration (ETp) was calculated using Penman-Montieth model. The actual evapotranspiration (ETa) was calculated using water balance equation and crop coefficient was calculated by dividing the ETa with ETp. The data obtained was analyzed statistically. The results of this study showed that grain yield and water use efficiency in wheat (Sahar-2006) was greatly improved by 23.4 and 15.0% (average of two years) under soil water deficit treatment I_3 (MMHMH) with potassium (K_2O applied at 300 kg ha^{-1}) as compared to regulated deficit treatment I_1 (HMLML) in combination without potassium (K_2O applied at 0 kg ha^{-1}). The optimum total irrigation water of 242.9 mm was distributed as 13.7 mm during germination stage, 22.15 mm during jointing, 21.10 mm during booting, 69.95 mm during heading, 58.9 mm during grain filling and 57.05 mm during maturity to fulfill the need of actual evapotranspiration which was required to produce the above mentioned increase in grain yield and other parameters. Root length and mass density were also increased by 35.9 and 35.6% in pot receiving I_3 (MMHMH) in combination with K_2 over I_1 (HMLML) in combination with K_0. K nutrition helped in mitigating the negative effects of water stress due to well-developed root system and accelerated the maximum water uptake and improved water use efficiency.

Keywords: Wheat, water use efficiency, regulated deficit irrigation, actual evapotranspiration, crop coefficient

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important and extensively grown cereal crops in the world. It is grown for its grains and straw and area under its cultivation is about 228 million hectare around the world. In area and production it ranks first at global level and is staple food for about one third population of the world (Anonymous, 2012-13). In Pakistan it is also consumed as a staple food (Anonymous, 2012-13). Soil moisture is considered as one of the most significant factors for poor yield of wheat. Low crop water productivity of wheat (0.6-1.7 kg m^{-3}) offers incredible opportunities for increasing or at least maintaining production of agricultural crops with a less amount of water (Zwart and Bastiaanssen, 2004).

One possible way to maximize yields per drop of water is the regulated deficit irrigation (RDI) (English and Raja, 1996). Saved water benefits are more significant than the losses of yield reduction by deficit irrigation especially in areas where water availability is limited (Eck *et al*., 1987). There is a linear relation between crop growth and irrigation levels. Water deficit at jointing (50-60% of field capacity) and at both booting and heading (65-70% of field capacity) followed by late reproductive period (50-60 % of field capacity) resulted in 25% increase in yield of wheat (Alderfasi and Refay, 2010). Number of irrigations affected the root length density and decreased irrigation frequency increased the root length density (Quanqi *et al*., 2010). Soil moisture deficit has significant effect on grain yield and water use efficiency with increasing soil moisture deficit

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reducing the yield of wheat but increasing the water use efficiency (Mahamed *et al*., 2011, Hamed *et al*., 2015).

The second most important factor which affects the water use efficiency is the evapotranspiration (ET) which consists of evaporation from soil surface and transpiration from plant. Statistically non-significant difference in ET was observed when single irrigation was applied at jointing, two irrigations at jointing and heading and three irrigations at jointing-heading-milking stages (Quanqi *et al*., 2010; Du *et al*., 2010). Around 20% of applied water was lost from soil through evaporation. So 40% of the applied water can be saved form loss through evaporation with two time partial root zone irrigation (Tang *et al*., 2010). They also reported that only 48-57% applied water was used in transpiration by crop during all irrigation practices. The water required for highest wheat yield was 300 mm with ET value 426 mm. Above this value of ET, irrigation requirement increased without increase in yield (Sun *et al*., 2006). The wheat grain yield increased when observed ET ranged from 415 to 460 mm. After that decline in yield was observed (Zhang *et al*., 2005). They also observed 16% reduction in ET with 59 mm less irrigation under regulated deficit irrigation. Irrigation significantly influenced the transpiration, evaporation and canopy temperature of wheat crop. ET was significantly increased with increasing amount of water applied and number of irrigations (Xue *et al*., 2003; Qiu *et al*., 2008; Gao *et al*., 2014). The water use efficiency had quadratic relation with ET and it decreased with increasing the volume of irrigation (Li *et al*., 2003).

The crop coefficient (Kc) is the most important factor in proper irrigation management. This is mostly used to estimate the crop water requirement and irrigation scheduling (Ko *et al*., 2009). In Pakistan, there is no work on the evaluation of crop coefficient developed Doorenbos and Pruitt (1977). This methodology provides simple tool for the prediction of crop evapotranspiration (ETc) and guide for irrigation scheduling. The determination of Kc using the on-site microclimatic data enables to calculate the crop water use and propagation of this information to the farmers in a trustworthy, serviceable and cheap manner.

Under regulated deficit irrigation, potassium (K) fertilization increase crop tolerance to water stress by utilizing the soil moisture more efficiently than in K deficient plants. The increase in the stress tolerance by K fertilization may be due to promotion of root growth associated with more nutrient and water uptake (Umar and Din, 2002) and through the reduction of transpirational water loss. It also maintains the osmotic and turgor of the cell and regulates the stomatal functioning under water stress condition (Kant and Kafkafi, 2002), which is reflected in improved crop yield under drought conditions. Under stress condition, K application promotes photosynthetic rate, plant growth and yield (Egila *et al*., 2001; Umar and Din, 2002).

Keeping in view the above facts, this study was conducted for assessing yield and WUE under regulated deficit irrigation at three levels of potassium that was K_0: 0 kg ha^{-1} K_2O, K_1: 200 kg ha^{-1} K_2O and K_2 : 300 kg ha^{-1} K_2O, respectively, and to calculate the K_c and ET_a value for wheat crop at different stages.

Materials and Methods

Pot experiments were conducted at the experimental farm of the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan (Latitude, 31°-26' N and 73°-06' E, 184 m ASL) during the winter seasons of 2010-11 and 2011-12. The climate of the study area is semi subtropical-arid with more than 70% of the annual rainfall occurring during June to September. Plastic pot having capacity of 9 kg soil was used as weighing lysimeter. Each pot had 25 and 11cm height and radius, respectively. Data showed (Table 1) that the soil type used for filling pot as well-drained Hafizabad sandy clay loam, mixed, semi-active, isohyperthermic Typic Calciargids. The bulk density of soil was maintained as 1.41 Mg m^{-3} during pot filling. The soil organic content was 0.52%. Retention capacity of soil was measured by determining water contents at pre-defined matric potential (Dane and Hopmans, 2002) with the help of suction plates at 0.3, 0.6, 1.0, 3.0 and 4.5 bar pressure and a linear regression equation was determined by taking ln (h) versus ln θ/θ_s to get water contents at permanent wilting point (θ_{WP}) and field capacity (θ_{FC}) of different soils (Williams *et al*., 1983). The following equation was developed by taking $ln\ \theta/\theta_s$ versus $ln\ (h)$ to get $\theta_{WP,}$ θ_{FC}, θ_{AWC} etc.

$$\ln P = \ln P_\alpha + b \ln (\vartheta / \vartheta_s) \qquad (1)$$

P is the matric potential (k Pa), "P_e" (intercept) is air entry value/bubbling pressure which is inversely related to "α", and "b" is the slope of $ln\ P$ vs $ln\ \theta/\theta_s$ of water retention curve.

The linear relationship between $ln\ \theta/\theta_s$ [-] and $ln\ (P)$ [kPa] were observed for the experimental soil with an air entry value (intercept) 0.0933 and a negative slope -7.9612 (Figure 1). Some selected physical and water retention properties of the soil are presented in Table 1.

Pot experiment was laid out in CRD having two factors (Regulated deficit irrigation X Potassium fertilizer) with two factorial arrangements. Three regulated deficit irrigation (RDI) treatments designed to subject the wheat crop to various levels of soil water deficit at different stages of crop growth and development were established and potassium fertilizer was also applied according to the

Table 1: Measured soil physical and hydraulic parameters of the experimental Soil

Particle size fraction (%)			BD	θ_s	θ_{FC}	θ_{PWP}	θ_{AWC}	K_s	SOC
sand	silt	clay*	(Mg m^{-3})	------------------cm^3 cm^{-3}	------------------------------			Cm day^{-1}	(%)
52.09±0.16	22.33±0.13	25.58±0.16	1.41±0.03	0.463±0.03	0.288±0.01	0.164±0.03	0.124±0.04	32±1.8	0.52±0.01

* Texture was loam according to USDA system ¶Mean± standard error (data are average of three repeats)

Table 2: Treatments (Irrigation and potassium levels) applied to the experimental units during the 2010-11 and 2011-12

Treatment	Potassium Level	Irrigation Level**	Jointing*	Booting	Heading	Filling	Maturity
T_1	K_0: No	I_1 (HMLML)	80 - 100	70 - 80	60 - 70	70 - 80	60 - 70
T_2	potassium	I_2 (MLLHM)	70 - 80	60 - 70	60 - 70	80 -100	70 - 80
T_3		I_3 (MMHMH)	70 - 80	70 - 80	80 - 100	70 - 80	80 - 100
T_4	K_1: 200 kg ha^{-1}	I_1 (HMLML)	80 - 100	70 - 80	60 - 70	70 - 80	60 - 70
T_5	K_2O	I_2 (MLLHM)	70 - 80	60 - 70	60 - 70	80 -100	70 - 80
T_6		I_3 (MMHMH)	70 - 80	70 - 80	80 - 100	70 - 80	80 - 100
T_7	K_2:300 kg ha^{-1}	I_1 (HMLML)	80 - 100	70 - 80	60 - 70	70 - 80	60 - 70
T_8	K_2O	I_2 (MLLHM)	70 - 80	60 - 70	60 - 70	80 -100	70 - 80
T_9		I_3 (MMHMH)	70 - 80	70 - 80	80 - 100	70 - 80	80 - 100

* The growing season was divided into six periods such as early development stage: germination (0-15 DAS), middle development stage: jointing (15-45DAS), late development stage: booting (45-60 DAS), early reproductive stage: heading (60-90DAS), middle reproductive stage: Grain filling (90-112 DAS) and late reproductive stage: Maturity stage (112-140 DAS). DAS stand, for days after sowing.

** Soil moisture of no- soil- water- deficit (H), medium soil water deficit (M) and severe water deficit (L) was maintained at above mentioned stages. When soil moisture varied out of the designed range, water was applied immediately to the top of the range. The designed range were H (80-100 % of AWC) 80% of AWC is lower range and 100% of AWC is upper for this treatment. Similarly in other two treatments M (70-80% of AWC) and L (60-70% of AWC). Below 60% of available water content moisture stress started so treatment was designed above this limit.

treatment plan (Table 2: Description of treatments). Each treatment was replicated three times. During the two growing seasons, controlled irrigation was applied to each pot by weighing pot on daily basis using weighing balance, so as to accurately maintain the soil water deficit levels followed by the above experimental design. Locally manufactured digital balance was used for weighing. It had weighing capacity in range from 200-30000 $\pm$ 5g. Data was collected according to Dwyer *et al*. (1987) and the irrigation amount was calculated to replace the depleted water content from each pot according to designed treatments. Local high yielding wheat variety Sahar-2006 was planted. The sowing time was November 20, 2010 and November 25, 2011. Urea was applied at the rate of 120 kg N ha^{-1} in two splits while phosphorus was applied at 85 kg ha^{-1} and potassium was applied according to treatment plan at the time of sowing. Seedling density after germination was controlled to 4 plants per pot. Weeds were removed effectively by hand during both growing seasons. Pests and diseases were also effectively controlled by pesticides in time. All the plants were harvested on April 13 during 2010-11 and April 09 during 2011-12. Based on soil water measurements from Pot by weighing method, the Actual Evapotranspiration was calculated using water balance equation:

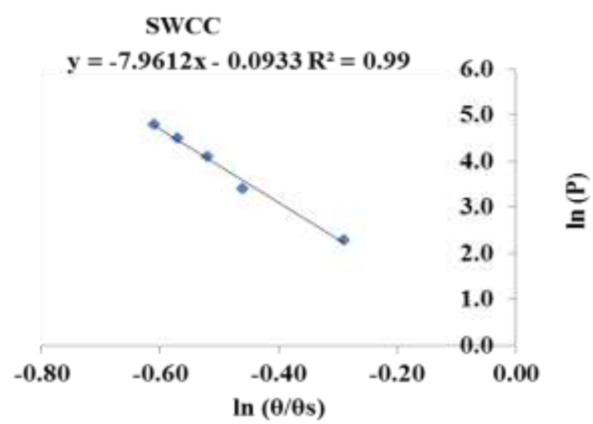

Figure 1: Determination of soil water characteristic curve of the experimental soil

$$ET_a = (I + p) - \Delta S \quad \textbf{(1)}$$

where ETa is the actual evapotranspiration (mm), I (mm) is irrigation, p (mm) is rainfall, and ΔS (mm) is change in root zone storage. There was no excess water losses below the root zone because the calculated volume of irrigation was applied in the root zone and pots were closed at the bottom. The crop coefficient was calculated as follows:

$$K_c = ET_a / ET_0 \quad (2)$$

where ETa and ET_0 stand for the actual evapotranspiration and potential evapotranspiration of the specific stage for which Kc was calculated. Daily reference/potential evapotranspiration (ET_0) for a hypothetical crop (Figure 2) was calculated using the Penman-Monteith FAO-56 Equation (Allen *et al.*, 1998) as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where ET_0 is the reference/potential evapotranspiration (mm day^{-1}), R_n the net radiation reaching the crop surface (M Jm^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychometric constant (k Pa $°C^{-1}$), T_{mean} the average daily air temperature measured at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s-e_a the saturation vapour pressure deficit (k Pa), e_a the actual vapour pressure (k Pa), e_s the saturation vapour pressure (k Pa) and Δ the slope of the vapour pressure curve (k Pa $°C^{-1}$).

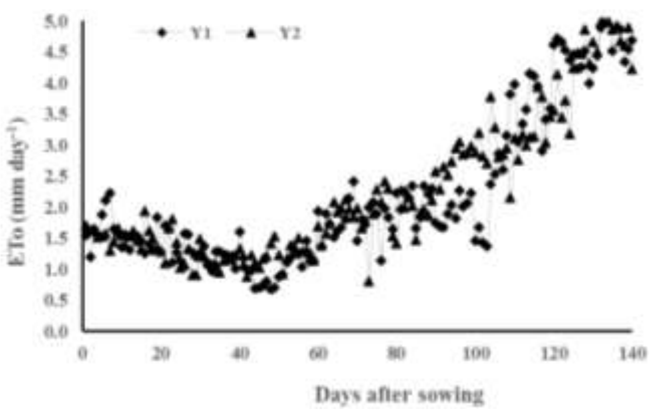

Figure 2: Determination of potential evapotranspiration of experimental area during 2010-11 (y1) and 2011-12 (y2)

At the end of growing seasons (April 13, 2011 and April 9, 2012), each pot was harvested for biomass, grain yield, root length density and root mass density. Harvest index was calculated as grain yield divided by mature crop biomass. Water-use efficiency was calculated as follows (Hussain *et al.*, 1995):

$$WUE = \frac{GY}{ET_a} \quad (4)$$

Where WUE (kg m^{-3}) is the water use efficiency for grain yield, GY is the grain yield (kg) and ET_a (m^3) is the actual evapotranspiration. Differences between treatments were examined using ANOVA (R-Software). The degree of association between different traits was also estimated through linear or non-linear regression models of the same statistical package.

Results

Grain yield, actual evapotranspiration and water use efficiency of wheat

The regulated deficit irrigation had significant effect on grain yield, seasonal actual evapotranspiration (ETa) and water use efficiency (WUE) with or without potassium fertilizer application (Table 3). Compared to the I_1 (HMLML) in combination with K_0 (No potassium was applied), regulated soil water deficit treatment along with or without potassium application improved the grain yield. The treatment combination I_3 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}) showed the highest increase in grain yield that was 21.38 and 25.45% over I_1 (HMLML) along with K_0 (No potassium), respectively, in growing seasons 2010-11 and 2011-12. The second best treatment was again I_3 (MMHMH) in combination with K_1 (K_2O at 200 kg ha^{-1}) that showed 18.36% increase in 2010-11 and 15.37% increase in 2011-12 over T_1 (HMLML) in combination with K_0 (No potassium). In this study, the highest grain yield was attained in treatment T_9 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}) which was subjected to medium soil water deficit at the jointing, booting and filling stages while no soil water deficit at the heading and maturity stage. Three linear functions were fitted through regression analysis among the data from grain yield, total biomass and harvest index under regulated deficit irrigation (Table 4) while regression analysis was non-significant in case of interaction of regulated deficit irrigation and potassium and main effect of potassium. Grain yield increased linearly with the biomass and harvest index, and increase in both biomass and harvest index under different levels of regulated deficit irrigation was result of the increase in both total biomass and harvest index.

In case of seasonal actual evapotranspiration (Table 3), the ETa ranged from 206.8-235.1 and 219.7-250.5 mm, respectively, during 2010-11 and 2011-12 in winter seasons. The maximum Eta was observed in treatment I_1 (HMLML) in combination with K_2 (K_2O at 300 kg ha^{-1}) in 2010-11 while I_3 (MMHMH) in combination with K_2 (Potassium at 300 kg ha^{-1}) showed the highest ETa in 2011-12 but both treatments were statistically at par during both years.

Significances occurred in water use efficiency (WUE) between regulated deficit treatments in combination with different levels of potassium. It was observed from the data presented in Table 3 that the

Table 3: Grain yield, Biomass and harvest index of wheat subject to various treatments under pot experiment during 2010-11 and 2011-12

Treatment	Grain yield (Mg ha^{-1})			Actual evapotranspiration (mm)			Water use efficiency (kg m^{-3})		
	K_o	K_1	K_2	K_o	K_1	K_2	K_o	K_1	K_2
2010-11									
I_1 (HMLML)	1.87	1.92	2.00	218.8	230.6	235.1	0.94	0.92	0.94
I_2 (MLLHM)	1.96	2.02	2.10	206.8	210.5	213.7	1.04	1.06	1.09
I_3(MMHMH)	2.13	2.21	2.27	222.8	228	234	1.05	1.07	1.07
LSD($p \leq 0.05$)		0.27			0.55			0.03	
2011-12									
I_1 (HMLML)	1.82	1.90	1.92	232.8	245.7	250.5	0.86	0.85	0.84
I_2 (MLLHM)	1.91	2.00	2.02	219.7	224.4	227.6	0.96	0.98	0.98
I_3(MMHMH)	2.02	2.10	2.28	240.2	245.3	251.7	0.93	0.94	1.00
LSD($p \leq 0.05$)		0.12			0.59			0.04	

Table 4: Relationship of different variables under regulated deficit irrigation

	Yield	WUE	HI	Biomass	RMD
Water Use Efficiency	0.74**				
	(0.03)				
Harvest Index	0.86*	0.96*			
	(0.04)	(0.001)			
Biomass	0.96*	0.57**	0.68		
	(0.00)	(0.02)	(0.03)		
Root mass density	0.89*	0.97*	0.97*	0.72*	
	(0.02)	(0.01)	(0.01)	0.03	
Root length density	0.88*	0.98*	0.96*	0.72*	0.97*
	(0.02)	(0.03)	(0.01)	(0.03)	(0.001)

*Liner relationship, **Quadratic relationship, Upper values are R^2 values, Values in parenthesis are probability value at alpha 0.05

WUE values varied from 0.84 to 1.09 Kg m^{-3} in two years (2010-11 and 2011-12). The increase in WUE was observed (10.6-13.8 and 11.6-16.3%) with regulated deficit irrigation Treatments I_2 (MLLHM) and I_3 (MMHMH) in combination with K_0, K_1 and K_2 as compared to the I_1 (HMLML) in combination with K_0, respectively, during 2010-11 and 2011-12. While 0-2.1 and 1.2-2.3% decrease in WUE was recorded in RDI treatment I_1 (HMLML) in combination with K_1 and K_2, respectively, in growing seasons 2010-11 and 2011-12. The maximum WUE was recorded in treatment I_2 (MLLHM) and I_3 (MMHMH) in combination with K_2 which was 1.09 and 1.0 kg m^{-3} respectively in growing seasons 2010-11 and 2011-12 and both were statistically at par during both years.

The good relationship between WUE and the harvest index was linear while relationships between WUE and grain yield, biomass were quadratic under regulated deficit irrigation (Table 4). In our simulation, the highest WUE of 1.036 kg m^{-3} was attained as the grain yield approached the critical value of 9.01 g per pot around the 68.33% of the observed maximum grain yield. The simulated value of WUE was lower as compared to observed value. The results indicated that the maximum WUE was not recorded at the maximum grain yield but a little earlier before that. The WUE increased significantly with the increase in harvest index. It was also significantly increased with increase in grain yield until the critical value mentioned above occurred, followed by a condign decrease of WUE with increase in grain yield. Similar trend was observed in biomass and WUE relationship. At a low value of grain yield and biomass, WUE almost linearly increased until a relatively higher WUE was met, after which being a marginal increase of WUE till the critical values of grain yield and biomass reached.

Crop coefficient (Kc) and actual evapotranspiration (ETa) of wheat at six stages

Significant differences occurred among treatments regarding crop Kc and ETa at jointing, booting, heading, grain filling and maturity stages (Table 5 and 6). In 2010-

Table 5: Crop coefficient (Kc) of wheat subject to various treatments at six stages under pot experiment during 2010-11 and 2011-12

Treatment	Potassium levels	Irrigation levels	Germination	Heading	Jointing	Grain filling	Booting	Maturity
						2010-11		
T_1	K_0	I_1 (HMLML)	0.56	1.07	0.9	0.84	0.86	0.45
T_2	K_1	I_2 (MLLHM)	0.54	1.13	0.55	0.74	1.12	0.44
T_3	K_2	I_3(MMHMH)	0.56	1.13	0.57	1.05	1.12	0.44
T_4	K_0	I_1 (HMLML)	0.57	1.17	0.92	0.85	1.15	0.45
T_5	K_1	I_2 (MLLHM)	0.55	1.17	0.56	0.75	1.15	0.44
T_6	K_2	I_3 MMHMH)	0.57	1.17	0.58	1.06	1.15	0.45
T_7	K_0	I_1 (HMLML)	0.58	1.22	0.93	0.86	1.18	0.45
T_8	K_1	I_2 (MLLHM)	0.56	1.18	0.57	0.76	1.16	0.45
T_9	K_2	I_3(MMHMH)	0.58	1.22	0.59	1.08	1.17	0.46
LSD ($p \leq 0.05$)			ns	0.011	0.04	0.011	0.02	0.01
						2011-12		
T_1	K_0	I_1 (HMLML)	0.57	1.09	0.92	0.86	0.88	0.46
T_2	K_1	I_2 (MLLHM)	0.55	1.15	0.56	0.75	1.14	0.45
T_3	K_2	I_3(MMHMH)	0.57	1.15	0.58	1.07	1.14	0.45
T_4	K_0	I_1 (HMLML)	0.58	1.19	0.94	0.87	1.17	0.46
T_5	K_1	I_2 (MLLHM)	0.56	1.19	0.57	0.77	1.17	0.45
T_6	K_2	I_3 MMHMH)	0.58	1.19	0.59	1.08	1.17	0.46
T_7	K_0	I_1 (HMLML)	0.59	1.24	0.95	0.88	1.2	0.46
T_8	K_1	I_2 (MLLHM)	0.57	1.2	0.58	0.78	1.18	0.46
T_9	K_2	I_3 MMHMH)	0.59	1.24	0.6	1.1	1.19	0.47
LSD ($p \leq 0.05$)			ns	0.01	0.06	0.01	0.03	0.01

11 growing season, crop coefficient (Kc) and actual evapotranspiration (ETa) ranged from 0.55-0.93, 20.6-34.8 mm, 0.86-1.18, 13.9-19.1 mm, 1.07-1.22, 60.7-69.2 mm, 0.74-1.08, 35.4-51.7mm and 0.44-0.0.46, 55.6-58.1 mm respectively, at jointing, booting, heading, grain filling and maturity stage. The maximum Kc was recorded in I_1 (HMLML) in combination with K_2 (K_2O at 300 kg ha^{-1}) at jointing stage because 80-100 % of available water content was applied at this stage which promoted the full expansion of leaf and unlimited supply of water. So highest actual evapotranspiration was also occurred in this treatment at jointing which is the reason of highest Kc. At booting stages, Kc and ETa was statistically at par in regulated deficit irrigation Treatment I_1 (HMLML) and I_3 (MMHMH) while former was significantly differed from the I_2 (MLLHM) because at these stages I_1 (HMLML) and I_3 (MMHMH) received 70-80% of available water content. However, I_2 (MLLHM) received 60-70% of available water content. So the difference in water supply was expressed as difference in ETa and Kc. At heading stage, Kc and ETa was the maximum because crop attained its maximum height and full leaf development.

Regardless of the applications of water, plant extracts the available water content in 60-70% or above range to fulfill the demand of evapotranspiration. After heading stage, decline in crop coefficient (Kc) and actual evapotranspiration was observed and both parameters decreased at grain filling stage. However, the highest Kc and ETa was observed in regulated deficit treatment I_3 (MMHMH) in combination of all three levels of potassium as compared to the other treatments at grain filling stage because of more evapotranspiration in this treatment, might be due to slowl yellowing of leaves as visual difference noted between treatments at this stage. At maturity stage, actual evapotranspiration was reduced and potential evapotranspiration increased which result low Kc value. More than 80% leaves were wilt and photosynthesis stopped due to stomata closer. As can be seen from Table 5 and 6, similar trend was observed in crop coefficient and actual evapotranspiration in 2011-12 growing seasons.

Root mass (g cm^{-3}) and length density (cm cm^{-3})

Root mass and length density of wheat was significantly affected by irrigation and potassium levels during 2010-11 and 2011-12 (Table 7). Root mass density ranged from 0.76-1.02 and 0.73-1.0 g cm^{-3}, respectively, in growing seasons 2010-11 and 2011-12. The root mass was increased with regulated deficit

Table 6: Evapotranspiration (ETa) mm of wheat subject to various treatments at six stages under pot experiment during 2010-11 and 2011-12

Treatment	Potassium levels	Irrigation levels	Germination	Heading	Jointing	Grain filling	Booting	Maturity
					2010-11			
T_1	K_0	I_1(HMLML)	13.4	60.7	33.7	40.2	13.9	56.9
T_2	K_1	I_2 MLLHM)	13	64.1	20.6	35.4	18.1	55.6
T_3	K_2	I_3(MMHMH)	13.4	64.1	21.3	50.3	18.1	55.6
T_4	K_0	I_1 (HMLML)	13.7	66.3	34.4	40.7	18.6	56.9
T_5	K_1	I_2 (MLLHM)	13.2	66.3	20.9	35.9	18.6	55.6
T_6	K_2	I_3 MMHMH)	13.7	66.3	21.7	50.8	18.6	56.9
T_7	K_0	I_1 (HMLML)	13.9	69.2	34.8	41.2	19.1	56.9
T_8	K_1	I_2 (MLLHM)	13.4	66.9	21.3	36.4	18.8	56.9
T_9	K_2	I_3(MMHMH)	13.9	69.2	22.1	51.7	19	58.1
LSD ($p\leq0.05$)			0.04	0.11	0.18	0.19	0.05	0.22
					2011-12			
T_1	K_0	I_1 (HMLML)	13	62.1	34	51.7	17.2	54.8
T_2	K_1	I_2 (MLLHM)	12.5	65.6	20.7	45.1	22.2	53.6
T_3	K_2	I_3(MMHMH)	13	65.6	21.5	64.3	22.2	53.6
T_4	K_0	I_1 (HMLML)	13.2	67.8	34.8	52.3	22.8	54.8
T_5	K_1	I_2 (MLLHM)	12.8	67.8	21.1	46.3	22.8	53.6
T_6	K_2	I_3 MMHMH)	13.2	67.8	21.8	64.9	22.8	54.8
T_7	K_0	I_1 (HMLML)	13.5	70.7	35.2	52.9	23.4	54.8
T_8	K_1	I_2 (MLLHM)	13	68.4	21.5	46.9	23	54.8
T_9	K_2	I_3(MMHMH)	13.5	70.7	22.2	66.1	23.2	56
LSD($p\leq0.05$)			0.01	0.11	0.17	0.25	0.06	0.21

Table 7: Root mass density and root length density of wheat subject to various treatments under pot experiments during 2010-11 and 2011-12

Treatment	Root mass density (g cm^{-3})			Root length density (cm cm^{-3})		
	K_o	**K_1**	**K_2**	**K_o**	**K_1**	**K_2**
			2010-11			
I_1 (HMLML)	0.76	0.92	0.95	2.17	2.61	2.71
I_2 (MLLHM)	0.78	0.95	0.97	2.23	2.7	2.77
I_3(MMHMH)	0.82	0.99	1.02	2.34	2.84	2.91
LSD($p\leq$ 0.05)		0.083			0.074	
			2011-2012			
I_1 (HMLML)	0.73	0.76	0.88	2.07	2.17	2.51
I_2 (MLLHM)	0.76	0.8	0.93	2.18	2.28	2.64
I_3(MMHMH)	0.8	0.96	1	2.28	2.75	2.85
LSD ($p\leq$ 0.05)		0.052			0.079	

irrigation treatment in combination with three levels of potassium which ranged from 2.6 to 34.2 and 4.1 to 37.0 % as compared to regulated deficit irrigation treatment I_1 (HMLML) in combination with K_0 (No potassium was applied) in growing season 2010-11 and 2011-12, respectively. The regulated deficit irrigation treatment I_3 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}) showed the highest root mass density which was 34.2 and 37.0% more as compared to regulated deficit irrigation treatment I_1 (HMLML) in combination with K_0, respectively, in growing seasons 2010-11 and 2011-12. Such performance in root mass density was extremely similar to that root length density. Regulated deficit irrigation treatment in combination with three levels of potassium improved the root length density as compared to regulated deficit irrigation treatment I_1 (HMLML) in combination with K_0 in growing seasons 2010-11 and 2011-12. The treatment combination I_3 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}) showed the highest increase in root length density that was 34.1 and 37.7 % over I_1 (HMLML) in combination with K_0 in growing seasons 2010-11 and 2011-12, respectively. In this study, the highest root mass and length density were attained in treatment I_3 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}) which was subjected to medium soil water deficit at the jointing, booting and filling stages while no soil water deficit at the heading and maturity stage.

Root mass and length density increased linearly with the WUE and harvest index, and increase in both under different levels of regulated deficit irrigation was result of the increase in WUE and harvest index. Biomass and grain yield also linearly increased with the root mass and length density. The root mass density was also increased linearly with increase in root length density (Table 4).

Discussion

Grain yield was maximum in the regulated deficit irrigation treatment I_3 (MMHMH) in combination with K_2 (K_2O t 300 kg ha^{-1}) as compared to I_1 (HMLML) in combination with K_0 (No potassium was applied) in growing seasons 2010-11 and 2012. Since the highest grain yield was maintained in the regulated deficit irrigation treatment I_3 (MMHMH) in combination with K_2 (K_2O at 300 kg ha^{-1}), we assured that the optimum controlled soil water deficit treatment in this study would be: 70-80% of AWC at the jointing, booting and grain filling stage and 80-100% of AWC at heading and maturity in combination of Potassium (K_2O) at the rate of 300 Kg ha^{-1} and it was followed by K_2O level 200 Kg ha^{-1}. Thus, water resources could be scientifically saved through regulated deficit irrigation in combination with potassium without reduction of crop yield under semi-arid condition like Pakistan. Such results are in line with that from Alderfasi and Refay (2010) who reported that the irrigation at 100 and 150 mm of CPE was statistically at par with regard to growth characters and K rates influenced growth vigor mostly through leaf area and dry matter production. Work of Zhang *et al*. (2006) also supported the results of current study. The conclusions could be helpful for the sustainable agriculture development in arid and semi-arid regions of the world especially in country like Pakistan which has low per capita water availability.

There were significant differences among treatments I_1 (HMLML) with or without potassium and the regulated deficit treatment I_2 (MLLHM) and I_3 (MMHMH) with or without potassium in water use efficiency (WUE). Our results are in line with Du *et al*. (2010) who found that WUE enhanced by applying water deficit at planting–stem elongation stage. Water deficit at planting–stem elongation stage is the best choice for improved WUE and its increment also decreased with deficit irrigation. Severe water scarcity at seedling–stem elongation, stem elongation–booting and booting–milking reduced by 5.61, 9.25 and 10.07% WUE, respectively. Mild water deficit produced 21.5 % more grain yield at seedling–stem elongation and milking–harvesting stage but it decreased WUE by 3.22 and 3.64% (Quanqi *et al*., 2010; Karrou *et al*., 2012).

Crop coefficient (Kc) value of wheat was obtained by dividing the actual evapotranspiration (ETa) with potential evapotranspiration (ETp) and Kc and ETa both were presented in Table 4 and 5. The Kc values increased from germination to heading and this increase due to increase in ETa value and low ETp value. After heading stage the Kc value decreased gradually due to decrease in Eta and increase in ETp. However, previous work showed that Kc values varied by many factors such as location, seasons, crop height and management (Baille, 1996, Marin *et al.*, 2016). Our results are also supported by those of Doorenbos and Pruitt (1977) who divided the crop coefficient (K_c) curve into four stages: Initial, crop development, mid and end-season stages. Similarly, Li *et al*. (2003) calculated Kc values 0.55, 1.03, 1.19, and 0.65 for the initial, crop development, mid-season, and late-season stages, respectively. In other study, Kc values determined over the growing seasons varied from 0.1 to 1.7 for wheat (Ko *et al*., 2009). They reported that the development of regionally based and growth-stage-specific Kc helps in irrigation management and provides precise water applications. Evapotranspiration, an important aspect of water balance and a key factor to determine proper irrigation schedule and to improve water use efficiency in irrigated agriculture (Liu *et al*., 2002).

Root length and mass density are important parameters which determine the water and nutrient uptake from soil. Our results showed that the application of 70-80% available water at jointing, booting and grain filling stages and 80-100% of available water at heading and maturity in combination with potassium significantly enhanced the root length and mass density. Such results coincided with these from Xue *et al*. (2003) who reported that irrigation significantly affected the rooting pattern. They also observed increase in root length density with 3 times irrigation at jointing, heading and milking stage in soil profile $\leq$ 30 cm depth. The highest root length density was observed in soil profile > 30 cm depth with single irrigation at jointing stage (Quanqi *et al*., 2010). Previous studies also showed that soil drying at early stage stimulated root growth, particularly the root growth in the deeper soil profile (Zhang *et al*., 1998).

The relationship between harvest index and grain yield, biomass, WUE, root length density, root mass density were linear under regulated deficit irrigation. So were between biomass and grain yield, WUE and root length density, root mass density; root length density and grain yield, biomass; root mass density and grain yield, biomass; root length density and root mass density. However, the relationship between WUE and grain yield, biomass could be described by quadratic equations. These relationships predicted that the highest harvest index was associated with the maximum grain yield, biomass, WUE, root length and mass density while the maximum WUE was not associated with the highest grain yield and biomass which was controlled by soil moisture content and water consumption. However, because of different experimental conditions from the previous studies such conclusions above were partly supported by Zhang *et al*. (1998) and Kang *et al.* (2002). While the positive correlation of root weight density (RWD) and root length density (RLD) with proper irrigation (Sangakkara *et al*., 2010) is evident from many studies.

Conclusion

In most of the cases of seasonal drought or arid and semi-arid areas of the world, regulated deficit irrigation in combination with potassium has significant effect on yield increase and improving water use efficiency. This research explores the effectiveness of regulated deficit irrigation in combination with potassium on wheat in semi-arid environment. The optimum level of regulated deficit irrigation proved to be 70-80% of available water content at middle vegetative growth period (Jointing), the late vegetative periods (booting), middle reproductive period (grain filling) and 80-100% of available water content at the early reproductive period (heading), and late reproductive period (maturity), respectively, in combination with potassium at the rate of 300 Kg ha^{-1}.

The corresponding optimum actual evapotranspiration of 242.9 mm (average of two years to give a full consideration of the climatic variability) was distributed as following: 13.7 mm during germination stage, 22.15 mm during the middle vegetative stage (jointing), 21.10 mm during the late vegetative stage (booting), 69.95 mm during the early reproductive stage (heading), 58.9 mm during the middle reproductive stage (grain filling) and 57.05 mm during the late reproductive stage (maturity).

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