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# YIELD RESPONSE OF WHEAT (*Triticum aestivum* L.) TO DEFICIT AND REGULATED DEFICIT IRRIGATION UNDER ARID/SEMI-ARID CONDITIONS

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The objective of present research was to devise irrigation management techniques/practices for improved water use efficiency (WUE) and optimum wheat yield in water scarce conditions. Investigations with different irrigation regimes including: optimal, deficit (DI) and regulated deficit irrigation (RDI) at different crop growth stages were carried out on a deep loam soil for four crop seasons (2010-2014). The results showed that early vegetative/ crown root initiation followed by flowering/anthesis stage are highly sensitive to soil moisture stress and irrigation stress at these stages may reduce the yield from 12 to 20%. However, deficit applied at late vegetative/booting stage may provide an opportunity to save irrigation water with relatively lower grain yield reduction (9%), higher harvest index (2%) and grain based water use efficiency ($WUE_g$; 10%). The lower value of water production functions ($k_{y\,=}$ 0.51 ) in the treatment with water stress at booting/late vegetative growth stage also indicated recovery of the crop from stress, exhibiting less than proportional reductions in yield with reduced water use. Regulated deficit irrigation (50% of the crop water requirement) at grain formation may result in comparatively lower yield reduction (-6%) relative to full irrigation skipped at booting, the reduction in harvest index (-3%) without any substantial increase in $WUE_g$made it uneconomical.
**Keywords:** Wheat, water scarcity, water use efficiency, yield response factor, soil moisture.

## INTRODUCTION

Frequent droughts and scarcity of irrigation water supplies in arid/semi-arid areas prohibit sustainable crop production. Reports on global water scarcity (Bonsch *et al*., 2015) indicate that approximately two-third of the world population will be facing water scarcity of certain degree in near future. This water scarcity will adversely affect food security and sustainability by reducing crop production (Hanjra and Qureshi, 2010). A sizeable quantity of water can be saved by increasing water use efficiency/productivity through environmentally sustainable and socially acceptable irrigation methods/ technologies such as high efficiency irrigation systems and deficit (DI) or regulated deficit irrigation (RDI) management strategies. These techniques have been widely used in several countries as a valuable approach where water is limiting factor in crop production (Liu *et al*., 2015).

Unlike full irrigation (FI), deficit irrigation is a water management strategy used to increase water use efficiency (WUE) or water productivity (WP) either with water stress maintained at defined growth stage or throughout the crop growing cycle that have little impact on yield (Fereres and Soriano, 2007). The resulting yield reduction should be small enough compared to the benefits obtained by using the saved water to either bringing additional area under cultivation (Hanson *et al*., 2007) or irrigating other fields for which water might normally be insufficient to meet crop water demands under traditional irrigation practices. Similarly, regulated deficit irrigation (RDI) is the frequent irrigation with reduced amount of water at crop growth stages exposed to drought conditions under semi-humid or semi-arid environments (Leite *et al*., 2015).

Many researchers reported the strategy and benefits of deficit irrigation management for different crops (El-Mageed and Semida, 2015; Samperio *et al*., 2015). However, research and adoption of deficit irrigation management strategy has seldom been studied in Pakistan despite heavy reliance on irrigation for crop production. Since water is getting increasingly scarce, optimizing crop yields and WUE is imperatively needed. In irrigated systems this could be achieved by scheduling irrigation in such a way that inevitable water deficit periods coincide with the least sensitive crop growth stages thus avoiding water stress at critical growth stages. It seemed justified, therefore, to explore the possibility of saving irrigation water without compromising yield.

The present study was carried out to determine the impact of different irrigation regimes on yield and water productivity of wheat, and devise irrigation management techniques/practices to improve the yield component of biomass production under water-limiting conditions of arid/semi-arid environment.

## MATERIALS AND METHODS

Field experiments were conducted for four consecutive crop seasons (2010–2014), to determine the yield and water use efficiency (WUE) of wheat (*Triticum aestivum* L.) under varying irrigation water application levels. The study was conducted at experimental farm of the Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan. To ensure the homogeneity of the experimental field, soil samples (in triplicate), from nine different locations within the field were taken from 0-15, 15-30 and 30-60 cm soil depth. Results of the analysis given in Table 1 show that experimental field was almost homogeneous with respect to soil physical, chemical and hydrological properties.

**Table 1. Physical and chemical properties of the experimental plots at NIAB, Faisalabad.**

| Parameters | Soil Depth (cm) | | |
|---|---|---|---|
| | **0-15** | **15-30** | **30-60** |
| EC (dS $m^{-1}$) | 0.87±0.11 | 0.87±0.34 | 0.94±0.27 |
| pH | 8.82±0.15 | 8.63±0.22 | 8.59±0.34 |
| $CO_3$ (meq $l^{-1}$) | 0.67±0.20 | 0.53±0.23 | 0.55±0.20 |
| $HCO_3$ (meq $l^{-1}$) | 4.40±1.21 | 3.53±0.98 | 3.44±1.01 |
| Cl (meq $l^{-1}$) | 1.99±0.51 | 1.91±0.73 | 1.92±0.50 |
| Ca+Mg (meq $l^{-1}$) | 3.14±0.91 | 2.69±2.28 | 1.84±0.68 |
| Na (meq $l^{-1}$) | 1.33±0.29 | 1.42±0.31 | 1.55±0.28 |
| % sand | 40.75±2.98 | 39±2.43 | 45±3.53 |
| % clay | 27.0±3.05 | 24±1.92 | 20±2.24 |
| Soil texture | Loam | Loam | Loam |
| Bulk density(ρb;g $cm^{-3}$) | 1.48±0.13 | 1.42±0.17 | 1.40±0.11 |
| Saturation ($m^3$ $m^{-3}$) | 46.8±6.54 | 48.8±6.83 | 45.8±8.72 |
| Field capacity ($m^3$ $m^{-3}$) | 29.4±3.19 | 28.2±3.95 | 25.3±3.36 |
| Wilting point ($m^3$ $m^{-3}$) | 14.3±1.16 | 13.1±1.70 | 10.8±1.25 |
| Sat. hydraulic conductivity (mm $hr^{-1}$) | 7.37±1.13 | 9.54±1.53 | 12.2±2.23 |

[Individual value represents mean±SD of 27 values (3 sampling point × 3 replicated samples from each depth per sampling point.]

The experiments were performed in a randomized complete block and replicated thrice each with twenty four sub-plots. The spring wheat varieties i.e., Sehar-2006 (SHR), Faisalabad-2008 (FSD) and Lasani (LSN), largely grown in the area, were subjected to eight (8) irrigation regimes including; four irrigations (I-I-I-I) at four critical growth stages of the crop, one irrigation skipped at crown root initiation/tillering (O-I-I-I), at booting (I-O-I-I), anthesis (I-I-O-I), grain formation (I-I-I-O), 50 % application at booting (I-0.5I-I-I), 50 % application at grain filling (I-I-I-0.5I), and 50 % application both at booting and grain filling (I-0.5I-I-0.5I) stages. Wheat seed at 125 kg $ha^{-1}$ (90 percent germination) was sown with a drill at row-to-row spacing of 15 cm. Whole of the fertilizer as urea, diammonium phosphate (46 percent $P_2O_5$) and sulphate of potash was applied @ 120-100-60 kg NPK $ha^{-1}$ at seed bed preparation. Planting was carried out on 15th November for both 2010-11 and 2013-14 crop growing seasons while on 5th November during crop seasons 2011-12 and 2012-13. All agronomic practices (except irrigation treatments/soil moisture) such as weeding, intercultural practices and plant protection measures were kept uniform in all crop seasons and experimental plots. Irrigation water, collected in a tank (32 $m^3$ [4 x 4 x 2 m]), was pumped through a pipe system and the amount applied to each sub-plot was measured using a flow meter connected between the pump and delivery pipe line. Irrigation treatments were started immediately after crop planting by withholding or applying the irrigation for different treatments, as and when required. Crop evapotranspiration (ETc) for the each irrigation treatment and the cultivar was calculated using water balance approach which was analyzed seasonally and annually using the following equation

$$(I+P\pm\Delta S) = ETc+(R+D)$$

Where, P and I represent rainfall and irrigation, respectively. The term $(I + P \pm \Delta S)$ indicates the available water during the crop growing season. The term ETc + (D + R) represents water lost from the experimental plot.

At crop maturity, four sub-samples from 1 $m^2$ area were taken from each treatment plot in a replicate. Total above ground biomass (B), grain yield (Y) and harvest index (HI) were determined. The average of above-mentioned four sub-samples for studied parameters was taken as representative of respective treatment plot in a replicate for further statistical analysis. Water use efficiency, biomass-based ($WUE_b$) as well as grain-based ($WUE_g$), were calculated as the ratio of biomass and grain yield to seasonal crop evapotranspiration (kg $ha^{-1}mm^{-1}$). Fisher's Analysis of Variance Technique was used for statistical analysis of all the data. Statistical comparisons between irrigation treatments (T), cultivars (C) and irrigation × cultivar (T×C) interactions for individual study year (Yr) were made. Four-year combined comparisons were also made for T, C, Yr, T×C, T×Yr, C×Yr and T×C×Yr. Least Significant Difference (LSD) test at 0.05 probability level was exercised to compare variances among treatment means (Steel *et al*., 1996). Statistical comparisons for mean values were considered significant at $p \leq 0.05$.

## RESULTS

***Soil moisture content at different growth stages*:** Soil water balance (ETc) for wheat growing seasons 2010-11 to 2013-14 was measured using data of soil moisture content (SMC) at crop planting and at physiological maturity, the level of water applied in different irrigation treatments, and the seasonal rainfall (Table 2). Highest SMC at crop harvest in different

**Table 2. Soil water contents (mm) at crop planting/physiological maturity, quantity of water applied at different irrigation levels (mm), growing season rainfall (mm) and soil water balance (ETc; mm) for wheat at NIAB, Faisalabad, over the growing seasons 2010-11 to 2013-14.**

| Components | Irrigation treatments* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ |
| **2010-11** | | | | | | | | |
| Soil water (planting) | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 |
| Soil water (maturity) | 144 | 149 | 152 | 129 | 135 | 144 | 139 | 141 |
| Irrigation | 185 | 135 | 135 | 135 | 155 | 160 | 170 | 145 |
| Precipitation | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| Final Balance/ETc | 310 | 255 | 252 | 275 | 289 | 285 | 300 | 273 |
| **2011-12** | | | | | | | | |
| Soil water (planting) | 202 | 202 | 202 | 202 | 202 | 202 | 202 | 202 |
| Soil water (maturity) | 156 | 173 | 157 | 149 | 145 | 156 | 150 | 148 |
| Irrigation | 230 | 170 | 170 | 180 | 180 | 200 | 205 | 175 |
| Precipitation | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| Final Balance/ETc | 284 | 207 | 223 | 241 | 245 | 254 | 265 | 237 |
| **2012-13** | | | | | | | | |
| Soil water (planting) | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 |
| Soil water (maturity) | 162 | 167 | 170 | 182 | 171 | 163 | 172 | 172 |
| Irrigation | 170 | 120 | 120 | 140 | 140 | 145 | 155 | 130 |
| Precipitation | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Final Balance/ETc | 308 | 253 | 250 | 258 | 269 | 282 | 283 | 258 |
| **2013-14** | | | | | | | | |
| Soil water (planting) | 204 | 204 | 204 | 204 | 204 | 204 | 204 | 204 |
| Soil water (maturity) | 156 | 150 | 135 | 136 | 130 | 155 | 155 | 136 |
| Irrigation | 210 | 160 | 160 | 160 | 170 | 185 | 190 | 165 |
| Precipitation | 53 | 53 | 53 | 53 | 53 | 53 | 53 | 53 |
| Final Balance/ETc | 311 | 267 | 282 | 281 | 297 | 287 | 292 | 286 |

*$T_1$ = I-I-I-I four irrigations at four critical growth stages; $T_2$ = O-I-I-I irrigation skipped at crown root initiation stage; $T_3$ = I-O-I-I irrigation skipped at booting stage; $T_4$ = I-I-O-I irrigation skipped at flowering stage; $T_5$ = I-I-I-O irrigation skipped at grain filling; $T_6$ = I-0.5I-I-I irrigation application corresponding to 50 %ETc at booting stage; $T_7$ = I-I-I-0.5I irrigation application corresponding to 50 %ETc at grain filling stage; $T_8$ = I-0.5I-I-0.5I irrigation application corresponding to 50 %ETc applied at both booting and grain formation

irrigation treatments (166-182 mm) was observed for crop season 2012-13. The range of SMC at harvest for the cropping seasons 2010-11 and 2013-14 was 129-152 mm and 130-156 mm, respectively. During 2011-12, in addition to the initial SMC at crop planting (202 mm), wheat growing season precipitation was also lowest (8 mm), which required relatively higher irrigation water application in different treatments; as a result, SMC at harvest in different irrigation treatments ranged from 148 to 157 mm. During different growing seasons, the crop evapotranspiration (ETc) in the control treatment (I-I-I-I) was almost similar (308-311 mm) except for the cropping season 2011-12 when it was relatively lower (284). The ETc in different deficit irrigation treatments was highest for cropping season 2013-14 (267-297 mm) and lowest for 2011-12 (207-245 mm). Comparing cropping seasons for ETc in regulated deficit irrigation treatments, the range was almost similar for 2010-11 (273-300 mm), 2012-13 (258-283 mm) and 2013-14 (286-292 mm), whereas relatively lower values were recorded for 2011-12 (237-265 mm).

***Biological yield*:** Analysis of variance (ANOVA) for biomass production indicated significant ($p \leq 0.05$) effect of deficit/regulated deficit irrigation as well as of cultivars in all study years (Table 3). Combined ANOVA also showed significant effects of irrigation treatments (T), cultivars (C) and study years (Y). However, interactions i.e., T×C, T×Y, C×Y and T×C×Y were all non-significant. Averaged across cultivars and cropping seasons, highest (21%) reduction in biological yield was recorded when irrigation was skipped at early vegetative (jointing) stage. The reduction in wheat biomass was relatively less (9-11%) when irrigation was skipped at late vegetative or at flowering stage, whereas minimum (5%) reduction was observed with irrigation skipped at late maturity stage. Applying regulated (50%) deficit irrigation at early vegetative stage compensated 14% of the biomass reduction caused by missing full irrigation. Regulating deficit irrigation (50%) at late maturity showed almost similar biomass yield as recorded with fully irrigated, or when the same irrigation was fully skipped. However, applying two regulated deficit irrigations (at early vegetative

**Table 3. All pair-wise comparison test for above ground biomass of wheat for irrigation treatment (T) and cultivar (C) in different study years (2010-13).**

| Treatments | Study Years | | | | Mean (treatment) |
|---|---|---|---|---|---|
| | 2010-11 | 2011-12 | 2012-13 | 2013-14 | |
| Irrigation treatment (T)* | | | | | |
| I-I-I-I | 14.12±1.40A | 14.76±1.41A | 15.04±1.20A | 13.63±1.29A | 14.39±1.39A |
| O-I-I-I | 11.38±1.03D (-19) | 10.47±0.65E (-29) | 13.13±1.04C (-13) | 10.30±0.67C (-24) | 11.32±1.41G (-21) |
| I-O-I-I | 12.43±1.11C (-12) | 13.06±1.47BCD (-11) | 13.68±1.06BC (-9) | 12.10±1.09B (-11) | 12.82±1.30E (-11) |
| I-I-O-I | 12.74±1.06BC (-10) | 12.20±1.24D (-17) | 14.62±0.98AB (-3) | 12.64±1.00AB (-7) | 13.05±1.40DE (-9) |
| I-I-I-O | 13.25±1.01ABC (-6) | 13.84±1.21AB (-6) | 14.19±0.93AB (-6) | 13.12±1.05AB (-4) | 13.60±1.11BC (-5) |
| I-0.5I-I-I | 13.13±1.17BC (-7) | 13.34±1.30BC (-10) | 14.14±1.14AB (-6) | 12.84±1.39AB (-6) | 13.36±1.30CD (-7) |
| I-I-I-0.5I | 13.49±1.18AB (-4) | 14.33±1.21A (-3) | 14.78±1.08A (-2) | 13.43±1.22A (-1) | 14.01±1.26AB (-3) |
| I-0.5I-I-0.5I | 12.91±1.38BC (-9) | 12.42±1.14CD (-16) | 14.56±1.24AB (-3) | 12.87±1.12AB (-6) | 13.19±1.43CDE (-8) |
| Cultivar (C) ‡ | | | | | |
| SHR | 13.77±1.27A | 13.82±1.62A | 14.74±1.09A | 13.16±1.56A | 13.87±1.50A |
| FSD | 12.11±1.12C | 12.04±1.52B | 13.46±1.09B | 11.91±1.21B | 12.38±1.38C |
| LSN | 12.91±1.14B | 13.30±1.62A | 14.60±0.98A | 12.78±1.33A | 13.40±1.46B |

*The values for irrigation are mean±SD of three cultivars each replicated three times; ‡The values for cultivar are mean±SD of eight irrigation treatments each replicated three times; Alphabets show the ranking of irrigation treatments and cultivars in a particular study year; Value in parenthesis is percent difference from I-I-I-I.

stage and at late maturity) showed much lesser yield reduction (8%) than when irrigation was fully skipped at early vegetative stage (21% reduction).

Irrigation treatment effects during different study years also showed highest yield reduction when irrigation was fully skipped at early vegetative stage (Table 3). However, negative effect of skipping this irrigation was relatively lower (13-19% reduction) during crop seasons 2010-11 and 2012-13 than that (24-29% reduction) recorded in 2011-12 and 2013-14. Besides, regulated (50%) deficit irrigation at this stage compensated the negative effects either fully (during 2012-13 and 2013-14) or partly (during 2010-11 and 2011-12; 7-10% reduction). In all study years, skipping (either full or 50%) irrigation at the late maturity though slightly reduced the biomass yield (1-6% reduction), the effect was statistically non-significant when compared with the unstressed treatment. Averaged across irrigation treatments and study years, highest biological yield was recorded for cv. Seher (SHR) followed closely by cv. Lasani (LSN), whereas cv. Faisalabad (FSD) produced minimum (Table 3). Averaged across irrigation treatments, highest biomass yield was recorded with cv. SHR during all study years, and with cv. LSN during 3 out of 4 years, whereas cv. FSD showed minimum yield in all study years.

***Grain yield*:** Averaged across cultivars and study years, highest (20%) reduction in grain yield was recorded when irrigation was skipped at early vegetative stage (tillering) i.e., first irrigation after planting ($p \leq 0.05$; Table 4). Skipping irrigations at late vegetative (booting), at flowering or at late maturity stages caused significantly lesser (9-12%) yield reduction. None of the regulated deficit irrigation treatments could produce grain yield at par with the unstressed treatment. However, comparing the grain yield reduction caused by skipping full irrigation at the tillering stage (20% reduction), yield reduction was significantly lower by skipping ½ irrigation at boot or at late maturity stages (6-8% reduction) or skipping ½+½ irrigations at boot plus late maturity stages (11% reduction). The response of grain yield to deficit/regulated irrigation varied in different cropping years. During 2010-11, skipping full irrigation at either growth stage caused almost similar reduction (9-15%) though yield became at par with the unstressed treatment when 50 % irrigation was applied at late vegetative stage. In growing season 2011-12, when yield reduction was highest (35%) with omitting irrigation at early growth stage, the reduction was much less (13-19%) with full irrigation skipped at any of the subsequent stages; the grain yield did not significantly improve with regulated deficit irrigation (RDI).

In crop season 2012-13 again, the highest reduction in grain yield was recorded with skipping irrigation at early growth stage though magnitude was much lesser than other study years (12% reduction vs. 15-35% reduction). Moreover,

**Table 4. All pair-wise comparison test for grain yield of wheat for irrigation treatment (T) and cultivar (C) in different study years (2010-13).**

| Treatment | Study Years | | | | Mean (treatment) |
|---|---|---|---|---|---|
| | 2010-11 | 2011-12 | 2012-13 | 2013-14 | |
| Irrigation treatment (T) | | | | | |
| I-I-I-I | 5.24±0.52A | 5.15±0.47A | 5.30±0.30A | 4.75±0.42A | 5.10±0.50A |
| O-I-I-I | 4.47±0.47D (-15) | 3.34±0.20F (-35) | 4.64±0.32C (-12) | 3.90±0.31D (-18) | 4.10±0.60E (-20) |
| I-O-I-I | 4.77±0.51BCD (-9) | 4.45±0.30BC (-13) | 4.95±0.25B (-6) | 4.37±0.42BC (-8) | 4.64±0.43C (-9) |
| I-I-O-I | 4.50±0.36D (-14) | 4.14±0.28DE (-19) | 5.15±0.40AB (-2) | 4.08±0.36CD (-14) | 4.50±0.55D (-12) |
| I-I-I-O | 4.52±0.38CD (-14) | 4.46±0.33BCD (-13) | 5.10±0.36AB (-3) | 4.34±0.35BC (-9) | 4.60±0.50CD (-10) |
| I-0.5I-I-I | 4.90±0.45AB (-6) | 4.35±0.47CD (-15) | 5.00±0.37AB (-4) | 4.40±0.40B (-7) | 4.70±0.50BC (-8) |
| I-I-I-0.5I | 4.84±0.33BC (-8) | 4.76±0.34B (-8) | 5.20±0.25AB (-1) | 4.45±0.35AB (-7) | 4.80±0.40B (-6) |
| I-0.5I-I-0.5I | 4.79±0.35BCD (-9) | 4.00±0.33E (-22) | 5.00±0.35AB (-5) | 4.35±0.40BC (-9) | 4.53±0.55CD (-11) |
| Cultivar (C) | | | | | |
| SHR | 5.03±0.51A | 4.42±0.61A | 5.20±0.30A | 4.56±0.43A | 4.80±0.57A |
| FSD | 4.42±0.38C | 4.14±0.55B | 4.80±0.25B | 4.03±0.35B | 4.35±0.51B |
| LSN | 4.81±0.36B | 4.45±0.58A | 5.15±0.34A | 4.40±0.35A | 4.70±0.50A |

during this year, even skipping full irrigation at early or late maturity did not significantly reduce the grain yield. During 2013-14, though deficit irrigation always produced less, 18% yield reduction caused by deficit irrigation at early growth stage was partly compensated when irrigation was skipped either at late growth stage (8 % reduction) or at late maturity (9% reduction).The grain yields in RDI treatments were though similar, saving 50% irrigation at late maturity was at par with unstressed treatment.

Averaged across cropping years and irrigation treatments, cv. SHR and LSN produced significantly higher grain yield than cv. FSD with almost similar trend during different cropping years (Table 4). Averaged across irrigation treatments, the grain yield was highly significantly correlated with the biological yield ($r=0.86$; $P<0.001$; $n=12$).

***Harvest index*:** Averaged across cultivars and study years, higher (5%) reduction in the harvest index (HI) was recorded when irrigation was skipped at early grain filling stage ($p\leq0.05$; Table 5) followed by flowering (4%), and regulated deficit irrigation (RDI) at grain filling and both at booting as well as grain filling (3%). Compared to the I-I-I-I (35.44±1.90%), irrigations skipped at early vegetative stage (tillering) i.e., first irrigation after planting or late vegetative (booting) had significantly higher HI of 36.25±3.52% and 36.22±2.38%, respectively. However, the difference between control and RDI at booting stage (I-0.5I-I-I; 35.03±2.50%) was non-significant. The response of HI to deficit/regulated irrigation varied in different cropping years. During crop seasons 2010-11, 2012-13 and 2013-14, skipping irrigation at early vegetative or booting stage resulted in higher biomass (3-9%). Compared to control, skipping/deficit irrigation at flowering or grain filling stages and RDI at grain filling resulted in lower HI ranging from 2 to 8%. Generally, regulated deficit treatments in these crop seasons showed non-significant differences from the control except for RDI applied both at booting as well as grain filling stages in 2013-14 for which significantly lower values of 33.7±1.30% were observed from the control (34.90±1.27%). However, in crop season 2011-12, skipping full irrigation either at early vegetative or grain filling stage and all RDI treatments resulted in significantly lower HI ranging from 4-8 %. The difference from the control (34.78±2.30 %) was non-significant in the treatments with deficit application at booting (34.40±3.20 %) and flowering stages (34.20±1.60 %).

Averaged across crop seasons and irrigation treatments, cv. FSD and LSN produced significantly higher HI than cv. SHR (Table 5). The difference among the cultivars was non-significant in crop seasons 2010-11 and 2012-13. However, in the year 2011-12 significant difference was observed with the values of 34.50±2.37, 33.38±1.47 and 31.80±2.0 % for cv. FSD, LSN and SHR, respectively. Similarly, the difference in HI for cop season 2013-14 was non-significant between cv. SHR (34.75±2.43 %) and LSN (34.54±2.22 %). The difference of cv. FSD (33.90±1.77%) was non-significant from cv. LSN and significant from cv. SHR.

**Table 5. All pair-wise comparison test for harvest index (%) of wheat for irrigation treatment (T) and cultivar (C) in different study years (2010-13).**

| Treatment | Study Years | | | | Mean (treatment) |
|---|---|---|---|---|---|
| | 2010-11 | 2011-12 | 2012-13 | 2013-14 | |
| Irrigation treatment (T) | | | | | |
| I-I-I-I | 36.89±1.45BCD | 34.78±2.30A | 35.20±1.92AB | 34.90±1.27BC | 35.44±1.90B |
| O-I-I-I | 39.44±2.92A | 32.11±2.10C | 35.60±2.07AB | 38.00±1.62A | 36.25±3.52A |
| | (70 | (-8) | -1 | -9 | -2 |
| I-O-I-I | 38.22±1.39AB | 34.40±3.20AB | 36.22±1.65A | 36.05±1.32B | 36.22±2.38A |
| | -4 | (-1) | -3 | -3 | -2 |
| I-I-O-I | 35.20±3.20DE | 34.20±1.60AB | 35.10±1.45AB | 32.21±1.40F | 33.80±2.30D |
| | (-5) | (-2) | 0 | (-8) | (-4) |
| I-I-I-O | 34.00±1.66E | 32.25±1.85C | 36.05±0.93A | 33.00±1.30EF | 34.20±2.05D |
| | (-8) | (-7) | -3 | (-5) | (-5) |
| I-0.5I-I-I | 37.60±0.88BC | 32.40±2.30C | 35.70±1.58A | 34.40±1.50CD | 35.03±2.50BC |
| | -2 | (-7) | -1 | (-1) | (-1) |
| I-I-I-0.5I | 36.00±1.58CD | 32.20±1.72BC | 35.10±1.27AB | 33.10±0.93EF | 34.35±1.85CD |
| | (-2) | (-4) | 0 | (-5) | (-3) |
| I-0.5I-I-0.5I | 37.22±1.92BC | 32.20±0.67C | 34.20±1.20B | 33.70±1.30DE | 34.33±2.25CD |
| | -1 | (-7) | (-3) | (-4) | (-3) |
| Cultivar (C) | | | | | |
| SHR | 36.54±2.80A | 31.80±2.00C | 35.13±1.33A | 34.75±2.43A | 34.55±2.77B |
| FSD | 36.62±2.30A | 34.50±2.37A | 35.80±1.90A | 34.00±1.77B | 35.20±3.32A |
| LSN | 37.29±2.46A | 33.38±1.47B | 35.33±1.50A | 34.54±2.22AB | 35.10±2.40A |

**Table 6. All pair-wise comparison test for water use efficiency (biomass) of wheat for irrigation treatment (T) and cultivar (C) in different study years (2010-13).**

| Treatments | Study Years | | | | Mean (treatment) |
|---|---|---|---|---|---|
| | 2010-11 | 2011-12 | 2012-13 | 2013-14 | |
| Irrigation treatment (T) | | | | | |
| I-I-I-I | 45.56±4.49B | 51.98±4.98C | 48.85±3.91D | 43.83±4.14A | 47.55±5.27DE |
| O-I-I-I | 44.61±4.04B | 50.57±3.13C | 51.91±4.12BCD | 38.56±2.52B | 46.41±6.34E |
| | (-2) | (-3) | -6 | (-12) | (-2) |
| I-O-I-I | 49.34±4.42A | 58.58±6.58A | 54.06±4.19AB | 42.91±3.87A | 51.22±7.52A |
| | -8 | -13 | -11 | (-2) | -8 |
| I-I-O-I | 46.32±3.87AB | 50.64±5.14C | 56.67±3.81A | 45.00±3.46A | 49.66±6.07ABC |
| | -2 | (-3) | -16 | -3 | -4 |
| I-I-I-O | 45.84±3.49AB | 56.49±4.94AB | 52.75±3.47BC | 44.16±3.54A | 49.81±6.32ABC |
| | -1 | -9 | -8 | -1 | -5 |
| I-0.5I-I-I | 46.08±4.10AB | 52.52±5.10C | 50.16±4.04CD | 44.74±4.85A | 48.37±5.38CD |
| | -1 | -1 | -3 | -2 | -2 |
| I-I-I-0.5I | 44.97±3.93B | 54.09±4.57BC | 52.22±3.82BCD | 46.00±4.17A | 49.32±5.59BCD |
| | (-1) | -4 | -7 | -5 | -4 |
| I-0.5I-I-0.5I | 47.30±5.04AB | 52.39±4.79C | 56.42±4.82A | 44.99±3.94A | 50.27±6.34AB |
| | -4 | -1 | -16 | -3 | -6 |
| Cultivar (C) | | | | | |
| SHR | 49.25±3.77A | 56.54±4.20A | 54.60±4.03A | 45.64±4.46A | 51.50±5.93A |
| FSD | 43.33±3.43C | 49.23±4.09B | 50.00±4.45B | 41.32±3.43B | 45.95±5.32C |
| LSN | 46.18±3.30B | 54.46±5.23A | 54.15±4.05A | 44.35±3.75A | 49.80±6.13B |

***Water use efficiency for biomass production*:** The data measured for biomass and seasonal crop ETc were used to calculate water use efficiency for biomass production (Table 6). The overall increase relative to the control was highest (8 %) when irrigation was skipped at late vegetative/booting stage (51.22±7.52 kg $ha^{-1}$ $mm^{-1}$) followed by non-significantly different $WUE_b$ of 49.66±6.07 and 49.81±6.32 kg $ha^{-1}$ $mm^{-1}$ when irrigation was skipped at flowering or late maturity stages, respectively.

The RDI at early vegetative stage improved the $WUE_b$ by 4 % compared to skipped irrigation at this stage and it was non-significantly different from RDI applied at late maturity stage. Skipping ½+½ irrigations at boot plus late maturity stages produced $WUE_b$ value at par with that for the DI applied at boot stage. Considering individual study years, applying DI at the booting stage always showed highest $WUE_b$, whereas treatments receiving DI at flowering or at grain filling also showed highest $WUE_b$ in 3 of the 4 study years.

Averaged across cropping years and irrigation treatments, cv. SHR (51.5±5.93 kg $ha^{-1}$ $mm^{-1}$) had significantly higher $WUE_b$followed by LSN (49.80±6.13 kg $ha^{-1}$ $mm^{-1}$) and FSD (45.95±5.32 kg $ha^{-1}$ $mm^{-1}$). The differences among the cultivars were significant in crop seasons 2010-11 with respective $WUE_b$ of 49.25±3.77, 46.18±3.30 and 43.33±3.43 kg $ha^{-1}$ $mm^{-1}$ for cv. SHR, LSN and FSD. In rest of the growing seasons, the difference between cv. SHR and LSN was non-significant compared to significantly lower $WUE_b$ for cv. FSD (Table 6). Averaged across cultivars and study years, the application of deficit (DI) or regulated deficit irrigation (RDI) management strategy generally resulted in higher water use efficiency for biomass production ($WUE_b$; kg $ha^{-1}$ $mm^{-1}$) except for the treatment with DI application at initial vegetative growth/tillering stage of the wheat crop. However, the difference for $WUE_b$ between control and DI at early vegetative stage of wheat (-2 %) was non-significant.

The overall increase, relative to the control, was highest (8 %) when irrigation was skipped at late vegetative/booting stage (51.22±7.52 kg $ha^{-1}$ $mm^{-1}$ ) followed by non-significantly different $WUE_b$ of 49.66±6.07 and 49.81±6.32 kg $ha^{-1}$ $mm^{-1}$ when irrigation was skipped at flowering or late maturity stages, respectively. The RDI at early vegetative stage improved the $WUE_b$ by 4 % compared to skipped irrigation at this stage and it was non-significantly different from RDI applied at late maturity stage. Skipping ½+½ irrigations at boot plus late maturity stages produced $WUE_b$value at par with that for the DI applied at boot stage.

***Water use efficiency for grain production*:** The data measured for wheat grain yield at harvest and seasonal crop ETc were used to calculate water use efficiency for grain production ($WUE_g$; kg $ha^{-1}$ $mm^{-1}$) presented in Table 7. Contrary to the $WUE_b$, the $WUE_g$ averaged across cultivars and study years was non-significantly different among deficit or regulated deficit irrigation except for the treatment with DI application at late vegetative growth/booting stage. The overall increase, relative to the control, was 10 % when irrigation was skipped at this stage (18.51±2.31 kg $ha^{-1}$ $mm^{-1}$). Considering individual study years, applying DI at the booting stage always showed higher $WUE_g$. As observed for $WUE_b$, treatments receiving full irrigation or that receiving DI at the tillering stage showed the lowest values of $WUE_g$.

Averaged across cropping years and irrigation treatments, cv. SHR (17.80±2.04 kg $ha^{-1}$ $mm^{-1}$) and LSN (17.45±1.91 kg $ha^{-1}$ $mm^{-1}$) produced significantly higher $WUE_g$ than cv. FSD (16.15±1.92 kg $ha^{-1}$ $mm^{-1}$). Comparing the individual study years, the differences in $WUE_g$ among the cultivars were

**Table 7. All pair-wise comparison test for water use efficiency (grain) of wheat for irrigation treatment (T) and cultivar (C) in different study years (2010-13).**

| Treatments | Study Years | | | | Mean |
|---|---|---|---|---|---|
| | 2010-11 | 2011-12 | 2012-13 | 2013-14 | (treatment) |
| Irrigation treatment (T) | | | | | |
| I-I-I-I | 16.90±1.67BCD | 18.12±1.67BC | 17.10±1.05D | 15.29±1.35A | 16.85±1.73BC |
| O-I-I-I | 17.52±1.83B | 16.13±0.99D | 18.36±1.25BC | 14.61±1.17A | 16.65±1.93C |
| | -4 | (-11) | -7 | (-4) | (-1) |
| I-O-I-I | 18.93±2.03A | 20.07±1.28A | 19.54±0.99A | 15.48±1.48A | 18.51±2.31A |
| | -12 | -11 | -14 | -1 | -10 |
| I-I-O-I | 16.32±1.29BCD | 17.20±1.14BCD | 19.98±1.61A | 14.53±1.28A | 17.01±2.37BC |
| | (-3) | (-5) | -17 | (-5) | -1 |
| I-I-I-O | 15.64±1.32D | 18.19±1.34B | 19.04±1.32AB | 14.61±1.21A | 16.87±2.22BC |
| | (-7) | 0 | -11 | (-4) | 0 |
| I-0.5I-I-I | 17.27±1.60BC | 17.13±1.84BCD | 17.85±1.33CD | 15.35±1.32A | 16.90±1.75BC |
| | -2 | (-5) | -4 | 0 | 0 |
| I-I-I-0.5I | 16.14±1.10CD | 17.96±1.27BC | 18.34±0.86BC | 15.22±1.28A | 16.91±1.70BC |
| | (-4) | (-1) | -7 | 0 | 0 |
| I-0.5I-I-0.5I | 17.53±1.71B | 16.91±1.38CD | 19.34±1.32AB | 15.18±1.45A | 17.24±2.06B |
| | -4 | (-7) | -13 | (-1) | -2 |
| Cultivar (C) | | | | | |
| SHR | 18.02±1.97A | 18.04±1.78A | 19.20±1.50A | 15.84±1.28A | 17.80±2.04A |
| FSD | 15.84±1.33C | 16.93±1.78B | 17.80±1.05B | 14.02±0.97B | 16.15±1.92B |
| LSN | 17.23±1.32B | 18.17±1.37A | 19.11±1.40A | 15.25±0.95A | 17.45±1.91A |

significant in crop season 2010-11 with respective values of 18.02±1.97, 17.23±1.32 and 15.84±1.33 kg $ha^{-1}$ $mm^{-1}$ for cv. SHR, LSN and FSD. In rest of the growing seasons, the difference between cv. SHR and LSN was non-significant, whereas significantly lower $WUE_g$ was calculated for cv. FSD.

## DISCUSSION

Although, crop yields are generally negatively affected by water deficit, the extent of damage varies with physiological stage exposed to water stress (Chaves and Oliveira, 2004). However, the response of crop yields to deficit irrigation showed variable trends in different studies. Galavi and Moghaddam (2012) recorded a 14 % reduction in grain yield when irrigation was skipped at the maximum tillering stage as compared to a 25% reduction caused by missing irrigation after flowering. Similarly, compared to well-watered wheat, applying water at 75% and 50% of the crop requirement caused grain yield reduction of 12% and 20%, respectively (Mugabe and Nyakatawa, 2000). However, (conforming to the results of an earlier study; Ali *et al*. (2007) in the present study, water deficit at an early stage was more harmful for the grain and biological yields as compared to deficit imposed at booting, flowering or grain filling stages.

Drought stress at an earlier physiological stage is known to adversely affect biomass accumulation in barley, wheat and maize by reducing the leaf area index and radiation use efficiency (Jamieson *et al*., 2010). On the other hand, water stress during grain filling stage is reported to enhance early senescence and shortens grain filling period (Yang and Zhang, 2006). However, early senescence accelerates the mobilization of stored carbohydrates thus avoiding negative effects on grain yield caused by the loss of photosynthesis due to shortening of the grain filling period under water stress (Zhang *et al*., 2006). Besides, in the present study, yield loss caused by skipping irrigation at the booting stage was probably also partly compensated by February rainfall, particularly during 2010-11 (38 mm) and 2012-13 (60 mm).

However, high WUE may be of little interest if it is not associated with high grain yield (Ali *et al*., 2007). In the present study, though fully irrigated treatment generally showed lower WUE and highest grain yield, skipping irrigation at the booting stage caused highest WUE that was associated with lowest yield reduction.

Considering the results it seems possible to save some quantity of irrigation water by reducing its application at booting stage of wheat crop. Averaged across study years, this treatment showed the highest WUE (18.5), saving 25 % of the water with a grain yield loss of 0.46 t $ha^{-1}$. The saved water would be available for an additional 0.25 ha, producing 1.16 t $ha^{-1}$ of additional grain, or a net extra yield of 0.7 t $ha^{-1}$. Although, net extra yield was slightly lower (0.65 t $ha^{-1}$) when irrigation was skipped at the grain filling stage, the WUE was also lower (16.9) than when irrigation was skipped at the booting stage. Besides, although RDI has been reported to be more advantageous over DI in saving water and in improving yield/water use efficiency (Zhang *et al*., 2006), reverse was observed in the present study. That is, saving 23 % of the irrigation water by skipping ½ irrigation each at the booting and grain filling stages was calculated to produce an extra 0.47 t $ha^{-1}$ of grain.

Yield response factor ($K_y$) is a basis to implement deficit irrigation strategy which can be calculated from the slope of regression line between relative evapotranspiration deficit and relative yield decrease at intercept set to origin (Doorenbos and Kassam, 1979) using the expression:

$$\left(1-\frac{Y_a}{Y_m}\right)=k_y\left(1-\frac{ET_a}{ET_m}\right)$$

where $Y_a$ (kg $ha^{-1}$) is the wheat yield measured from a particular deficit irrigation treatments with specific evapotranspiration $ET_a$ (mm) corresponding to $Y_a$. Whereas $ET_m$ (mm) and $Y_m$ (kg $ha^{-1}$) are the evapotranspiration and wheat yield of reference treatment i.e., the treatments without water deficit. The term $(1-\frac{Y_a}{Y_m})$ represents the relative yield decrease corresponding to relative evapotranspiration deficit$(1-\frac{ET_a}{ET_m})$. The relationship between the two is plotted in Figure 1.

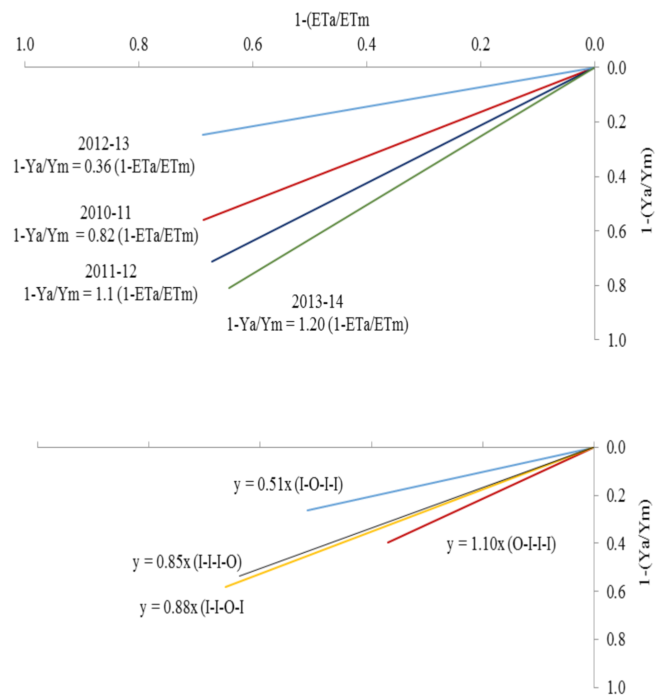


**Figure 1. Water production functions for wheat subjected to water deficits imposed during the crown root initiation/tillering (O-I-I-I), booting (I-O-I-I), flowering (I-I-O-I) and grain filling (I-I-I-O) stages.**

The data of different deficit irrigation treatments pooled across the years showed the yield response factor greater than unity ($k_y$>1) when water deficit was imposed on crown root initiation stage indicating higher sensitivity of the crop response to water deficit with proportional higher yield decrease. Generally, the yield response factor to water deficit in different study years when pooled across irrigation treatments was higher ($k_Y$=1.1) in the year receiving lower rainfall (8 mm in 2011-12). In crop season 2013-14, total growing season rainfall (53 mm), which was received at the end of crop growing season, did not contribute towards yield increase in deficit irrigation treatments thus resulting in higher $k_y$value of 1.20. For rest of the two growing seasons, the incident rainfall received at the higher moisture sensitive stages resulted in lower $k_y$ value.

A lower value of 0.51 ($k_y$< 1) in the treatment with water stress at booting/late vegetative growth stage showed a recovery of crop from stress, exhibiting less than proportional reductions in yield with reduced water use. Deficit imposed at flowering or grain filling stage had approximately similar mean $k_y$ values of 0.88 and 0.85, respectively. Similar relationship was reported by other researchers. For example, Doorenbos and Kassam (1979) reported $k_y$ value for spring wheat of 1.15 for total growing season, whereas Imtiyaz *et al*. (1982) estimated a higher $k_y$ (1.58) for spring wheat. The measured values ($k_y$<1) for deficit applied on booting stage showed a greater opportunity of water saving.

***Conclusion*****:** Results of the present study show that crown root initiation/early vegetative and flowering stages are more sensitive crop growth stages to moisture stress and irrigation stress at these stages greatly affect wheat production and productivity. However, irrigation water deficit at late vegetative/booting stage had comparatively lower grain yield reduction compared to biomass thus may improve harvest index and water use efficiency of wheat. Besides, since canal water is not available during this period, farmers have to rely on extraction of groundwater. Therefore, avoiding this irrigation will not only reduce the input cost without scarifying the yield, but will also reduce the environmental impact of fossil fuel consumed for extraction of groundwater as well as the ill effects of poor quality irrigation water on soil in the long term.

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