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Yield, Grain Protein Content and Input Use Efficiency in Wheat as Influenced by Irrigation and Nitrogen Levels in a Semi-arid Region

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A field experiment was conducted at ICAR-Indian Agricultural Research Institute, New Delhi during 2011-12 to 2012-13 to study the interactive effect of irrigation and nitrogen (N) fertilizer on yield, grain protein content, and water and N use efficiency of wheat. The design of the experiment was split-plot with irrigation (I_0: rainfed, I_2: two irrigations, I_3: three irrigations, I_5: five irrigations) as main plot and N (N_0: 0 kg N ha^{-1}, N_{30}: 30 kg N ha^{-1}, N_{60}: 60 kg N ha^{-1} and N_{120}: 120 kg N ha^{-1}) as sub-plot treatment. Averaged across the years, I_5 treatment registered 4, 33 and 192 per cent higher grain yield compared to I_3, I_2 and I_0 treatments, respectively. Similarly, N_{120} treatment registered 19, 42 and 93 per cent higher wheat grain yield compared to the N_{60}, N_{30} and N_0 treatments, respectively. The I_0 irrigation treatment registered 23, 25 and 16 per cent lower water use efficiency (WUE) compared to the I_2, I_3 and I_5 treatments, respectively. The I_5 irrigation treatment registered 3, 32 and 200 per cent higher partial factor productivity of N (PFP_N) compared to I_3, I_2 and I_0 treatments, respectively. Thus, wheat may be grown with three irrigations at crown root initiation, tillering and flowering stages with 120 kg N ha^{-1} for higher yield, grain protein content and WUE in the semi-arid environment of Delhi.

Key words: Wheat, yield, water use efficiency, grain protein content, nitrogen use efficiency

In India, wheat (*Triticum aestivum* L.) is the second most important cereal crop after rice covering an area of 30.97 million ha (Mha) with the production of 88.94 million tonnes (Mt) during 2014-15 (http://eands.dacnet.nic.in/). This crop being highly sensitive to water stress produces substantially low under water restricted environment and gives significantly higher yield with supplemental irrigation (Gajri *et al.* 1993; Hati *et al.* 2001; Bandyopadhyay *et al.* 2009; Karam *et al.* 2009; Bandyopadhyay *et al.* 2010; Pradhan *et al.* 2014a). Under intensive cropping system, the crop productivity and input use efficiency is primarily governed by the precise moisture level and fertilizer application. Day-by-day, the availability of water is becoming scarce because of increasing demand from domestic and industrial sectors jeopardizing the future food security of India. As wheat is being highly irrigation intensive with a requirement of 300 to 500 mm, needs assured irrigation to get optimum yield. So, there is an urgent need to enhance water productivity *i.e.*, to produce more food with less water for sustainable production. After irrigation, fertilizer-nitrogen (N) is the second most important input for proper crop growth and development and wheat is no exception. There is synergistic interaction between N and water on crop yields. If water is limited, N will be poorly utilized by crops. Many researchers observed that increased irrigation levels results in increased nitrogen uptake and thereby enhances nutrient use efficiency of wheat (Gajri *et al.* 1993; Bandyopadhyay *et al.* 2010). Similarly, higher water use efficiency has been achieved at higher levels of N applied in wheat (Husain and Aljaloud 1995; Pradhan *et al.* 2014a,b). On the other hand, excessive and indiscriminate use of these inputs leads to not only economic loss but also causes environmental pollution especially ground water contamination. Hence, it necessitates optimization of irrigation and N for highest input use efficiency without hampering crop yield.

Grain protein content is an important quality factor as it decides milling and baking quality in wheat

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and thereby its marketability. Application of N is reported to increase both yield and grain protein content (Gauer *et al.* 1992). Protein content is increased by N application above the point where N is no longer the yield limiting factor (Gauer *et al.* 1992). As the efficacy of N depends on availability of soil water, grain protein content is also indirectly related to soil moisture condition. However, increased yield due to improvement of soil moisture have been shown to reduce protein content of wheat due to dilution of N by larger biomass. So it necessitates optimization of irrigation and N not only for highest input use efficiency and yield but also for grain protein content. Keeping these in view, field experiments were undertaken to study the effect of irrigation and N on yield, grain protein content and input use efficiency of wheat in semi-arid environment of Delhi.

Materials and Methods

Study area

A field experiment was conducted during *rabi* (winter) 2011-12 and 2012-13 at the experimental farm of the ICAR-Indian Agricultural Research Institute, New Delhi (77°89' E, 28°37' N and 228.7 m above mean sea level) on wheat (*Triticum aestivum* L.). The area is placed under semi-arid subtropical climatic belt. It is characterized by extreme temperatures, the annual maximum temperature goes as high as 45 °C in summer, whereas the minimum temperature dips to as low as 1°C in winter. The mean annual rainfall is about 680 mm, of which 75% is received during monsoon periods of July to September. The soil is sandy loam (Typic Haplustept) with medium to angular blocky structure, non-calcareous and slightly alkaline in reaction. The soil is low in organic carbon (OC) and available N and medium in available P and K. The bulk density (BD) varied from 1.58 to 1.72 Mg m^{-3}, saturated hydraulic conductivity from 0.39 to 1.01 cm h^{-1} and saturated water content from 0.39 to 0.41 $m^3 m^{-3}$ in the upper 0-1.20 m soil layer. The soil moisture content was 26–29% at 0.033 MPa (field capacity) and 8–11% at 1.5 MPa (permanent wilting point) in different layers of 0 to 1.20 m soil depth.

Experimental details

The experiment was laid out in a split-plot design with irrigation levels as main plot treatments and N levels as subplot treatments, replicated thrice. The subplot size was 5 m×4 m. The irrigation levels were I_0: no irrigation or rainfed, I_2: two irrigations (crown root initiation (CRI) and flowering stages), I_3: three irrigations (CRI, tillering and flowering stages) and I_5: five irrigations (CRI, tillering, jointing, flowering and grain filling stage). In each irrigation, an amount of 60 mm water was applied through surface irrigation. The irrigation amount was measured by Parshall Flume. The amount of irrigation water applied for I_0, I_2, I_3 and I_5 were 0, 120, 180 and 300 mm and 0, 120, 180 and 240 mm for 2011-12 and 2012-13, respectively. The N levels were N_0: no N, N_{30}: 30 kg, N_{60}: 60 kg and N_{120}: 120 kg N ha^{-1}. Urea was used as source of N and was applied in two equal splits as basal and at CRI stage. Recommended basal dose of phosphorus (P) and potassium (K) @ 60 kg P_2O_5 ha^{-1} as single superphosphate and 60 kg K_2O ha^{-1} as muriate of potash, respectively was applied in all the plots. Wheat crop (cv. HD 2932) was sown on 18th and 21st November in 2011 and 2012, respectively, with a seed drill (at a depth of 4-5 cm) with a row spacing of 22.5 cm and seed rate of 100 kg ha^{-1} and harvested on 19th and 18th April 2012 and 2013, respectively. The plots were kept weed-free by hand weeding (twice). Also, the crop was kept free from insects and pathogen attack by taking appropriate control measures. Daily weather data were collected from meteorogical observatory of IARI, Delhi.

Soil moisture storage, evapo-transpiration (ET) and water use efficiency (WUE)

Soil moisture content in the profile (0-120 cm) was measured gravimetrically at the regular interval during crop growth period of 2011-12 and 2012-13 at 15 cm intervals up to 30 cm and at 30 cm increment up to 120 cm soil depth.

Seasonal evapo-transpiration (ET) was computed using the field water balance equation as given below:

$$ET = (P + I + C) - (R + D + \Delta S)$$

where, ET is the seasonal evapo-transpiration (mm), P is the precipitation (mm), I is the irrigation (mm), C is the capillary rise (mm), R is the runoff (mm), D is the deep percolation (mm) and ΔS is change in profile soil moisture (mm).

As the groundwater table was very deep (8–10 m), C was assumed to be negligible. There was no runoff (R) from the field plots and no bund overflow was observed during the period of study. As soil moisture was studied up to 120 cm and the profile was loamy with a clay loam layer having a high BD of 1.71–1.72 Mg m^{-3} below 60 cm, deep percolation out of the 120 cm profile (D) was assumed to be negligible.

Thus, $ET = (P + I) - \Delta S$

Evapo-transpiration production function (ETPF), the relation between wheat grain yield and seasonal evapo-transpiration was linear and was expressed as:

$Y = a + b \times ET$

where, 'Y' is the grain yield (kg ha^{-1}), 'a' is the intercept and 'b' is slope of the ETPF.

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was computed as: $WUE = \frac{Y}{ET}$

The net plot (5 m × 4 m) was harvested manually by cutting the plants close to the ground. The plant samples were dried and weighed for aboveground biomass yield and expressed in kg ha^{-1}. Threshing of wheat was done by mechanical thresher and the grain yield was expressed in kg ha^{-1}.

Thus, $WUE = b + \frac{a}{ET}$

i.e. marginal water use efficiency (MWUE), the differentiation of ETPF with respect to ET, *i.e.*, (dY/dET), was computed using the formula (Liu *et al.* 2002) as:

$$MWUE = \frac{dY}{dET} = b$$

where, b is the intercept of WUE *vs* 1/ET equation. WUE will increase with ET if a < 0, decrease with increasing ET if a > 0, and equal to MWUE if a = 0 (Liu *et al.* 2002).

The crop yield response factor (Ky) is an indication of crop's sensitiveness to water stress in a particular environmental condition. The Ky value greater than one indicates crop being sensitive to water deficit with larger proportional yield reductions under reduced water use conditions. The Ky value less than one means the crop is more tolerant to water deficit exhibiting less than proportional reductions in yield with reduced water use, while a value equal to one indicates that the yield reduction is directly proportional to reduced water use as evident from the following equation (Doorenbos and Kasam 1979):

$$1 - \frac{Y_a}{Y_m} = Ky(1 - \frac{ET_a}{ETm})$$

The yield response factor to drought (Ky) was determined by relating the relative yield decrease (1-Ya/Ym) to the corresponding relative evapo-transpiration deficit (1- ETa/ETm) where Ya and ETa represent the actual yield and the corresponding total actual seasonal evapotranspiration, and Ym and ETm represent the maximum yield and the corresponding seasonal evapotranspiration of the irrigation treatment.

Root analysis

Root samples were collected at flowering stage using core sampler of 15 cm height and 7 cm diameter at 15 cm depth increments up to a depth of 60 cm. The shoot of the plant was cut close to the soil and the soil surface was cleaned by removing unwanted materials if any. The collected soil cores were sealed in polythene bags, washed and processed in the laboratory. The lengths were recorded through the scanning and image analysis of the root skeleton. The root length was divided by the core volume to estimate root length density.

Nitrogen use efficiency and grain protein content

The N use efficiency was expressed in the form of partial factor productivity of N (PFP$_N$) as follows:

$$\text{Partial factor productivity of N (PFP}_\text{N}) = \frac{\text{Grain yield (kg ha}^{-1})}{\text{Total N applied (kg ha}^{-1})}$$

The protein content in grain was measured by grain analyzer through the spectroscopic investigations.

Statistical analysis

The data were statistically analyzed using analysis of variance as applicable to split plot design using SAS package. The significance of the treatment effects was determined using F-test, and the difference between the means was estimated using LSD and Duncan's multiple range tests at 5% probability level. Regression analyses were performed using the data analysis tool pack of MS Excel.

Results and Discussion

Weather parameters

The mean monthly air temperature, relative humidity, reference evapotranspiration (Allen *et al.* 1998), solar radiation and rainfall during the period of study are presented in table 1. Mean monthly temperatures were almost similar in both the years of study. Higher rainfall (183 mm) was received in 2012-13 as compared to 2011-12 (43 mm). During the second year, unexpectedly higher rainfall was received in the month of February (109.4 mm) than 2011-12 (0 mm), which coincided with the booting and flowering stage of wheat crop. The mean monthly relative humidity was 6-18 per cent higher in 2012-13 compared to 2011-12, except in December, where it

Table 1. Weather conditions during the study period

Months	Mean temperature (°C)	Mean relative humidity (%)	Total rainfall (mm)	Total solar radition (MJ m^{-2})	Total reference ET (mm)
2011-12					
November	20.7	61	0	348	72
December	14.2	67	0	298	50
January	12.1	73	14.8	326	53
February	15.3	54	0	459	93
March	21.3	50	19.2	582	140
April	27.4	40	9	655	168
2012-13					
November	18.6	76	0	319	55
December	14.6	49	8.6	326	61
January	11.4	79	40.8	333	48
February	15.8	72	109.4	397	67
March	21.8	61	12.6	629	137
April	27.7	47	11.6	692	183

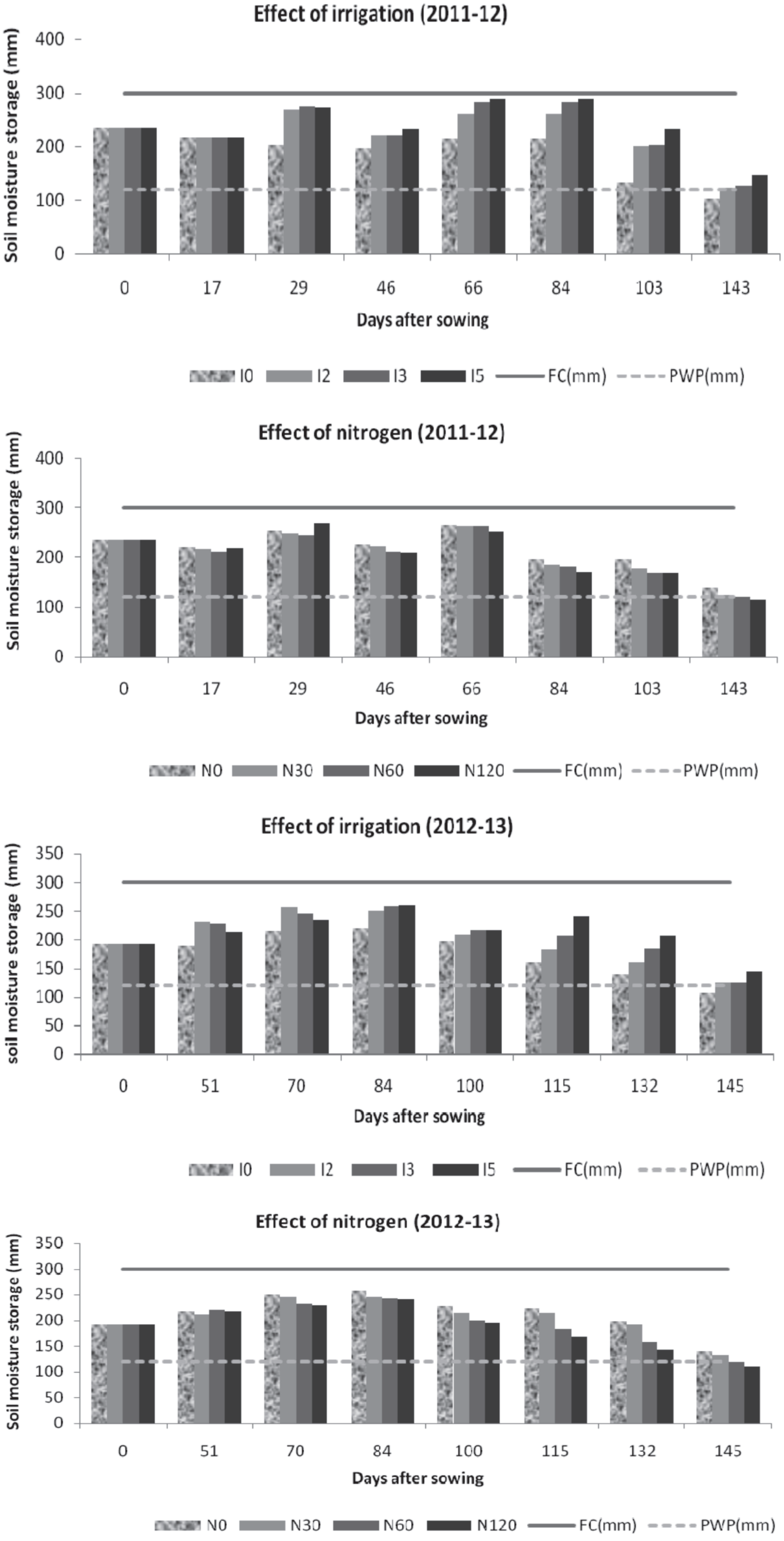
was 18 per cent lower. The higher mean monthly relative humidity can be attributed to the higher rainfall of the year. The total monthly solar radiation was almost similar in both the years except for February, 2012-13, where it was 62 MJ m^{-2} lower than the year 2011-12. The reference evapotranspiration during February 2012-13 was 26 mm lower than that in 2011-12, which can be attributed to the lower solar radiation, higher rainfall and higher relative humidity during February 2012-13. In general, the crop during 2011-12 experienced more congenial environment throughout the growth period compared to the second year.

Soil moisture dynamics

Temporal variations in soil moisture storage in the profile (0-120 cm) for irrigation and N treatments for both the years of study are presented in fig. 1. The peaks in the soil moisture storage both for irrigation and N treatments at different periods of observation correspond to either rainfall or irrigation events. The soil moisture storage in the irrigation treatments increased (after 29 DAS during 2011-12 and 84 DAS in 2012-13) with increase in irrigation levels. The delay in observation of irrigation effect on soil moisture storage may be attributed to the higher and well distributed rainfall (150.2 mm in 7 spells) during 2012-13. However, throughout the crop growth period, the soil moisture storage for all the irrigation treatments except the rainfed treatment at harvesting stage of both the years remained well within the field capacity (FC) and permanent wilting point (PWP) (Fig. 1). Prolonged water deficit due to either scanty rainfall or no irrigation in rainfed treatment probably forced crops to extract water below PWP to meet the demand of evapo-transpiration. According to Pradhan *et al.* (2014a), the soil moisture storage below PWP at harvesting stage of wheat was due to absence of water input. Similar to irrigation treatments, the soil moisture storage of N treatments except for N_{120} at harvesting stage of both the years of study also remained well within the FC and PWP. At peak and later growth stages, the soil moisture storage decreased with increase in N levels (Fig. 1). It may be attributed to better crop and root growth and correspondingly higher uptake of water by the crop. In an earlier study on wheat (Pradhan *et al.* 2014a), a lower soil moisture storage was observed at higher level of N application due to better crop growth and hence higher water loss through evapotranspiration in an Inceptisol. Hati *et al.* (2001) also observed higher uptake of soil moisture in fertilized crop compared to unfertilized one due to better crop and root growth in a Vertisol. Bandyopadhyay *et al.* (2010) found higher evapo-transpiration and hence lower soil moisture storage in integrated nutrient management treatment compared to either chemical or FYM treatment due to higher aboveground biomass and root proliferation.

Seasonal evapotranspiration (ET)

The seasonal evapotranspiration (ET) among all the treatments varied from 136 (I_0N_0) to 446 mm (I_5N_{120}) during 2011-12 with a mean value of 301 mm, and 237 (I_0N_0) to 488 mm (I_5N_{120}) with a mean value of 385 mm in 2012-13. The water input


Effect of irrigation (2011-12)

Effect of nitrogen (2011-12)

Effect of irrigation (2012-13)

Effect of nitrogen (2012-13)

Fig. 1. Temporal variation in soil moisture storage during wheat crop growth for irrigation and nitrogen treatments (2011-12 and 2012-13)

(irrigation + rainfall) into the soil profile during 2012-13 was higher than that in 2011-12 because of higher rainfall during the second year (Table 1). Hence, more water was available for evaporation and transpiration during 2012-13, which resulted in 28 per cent higher ET in 2012-13 compared to 2011-12.

Averaged over the N treatments, ET increased significantly with the increase in irrigation treatments for both the years (Table 2). The ET for the year 2011-12 was the highest in I_5 treatment (430 mm) followed by I_3 (354 mm), I_2 (272 mm) and I_0 (150 mm). The ET for the year 2012-13 also followed a trend similar to the year 2011-12 *i.e.*, 471 mm in I_5, 449 mm in I_3, 371 mm in I_2 and 250 mm in I_0. Averaged over the years, I_5 registered 12, 40 and 126 per cent higher ET compared to the I_3, I_2 and I_0 treatments, respectively (Table 2). The increased in ET with increase in irrigation levels could be attributed to the higher water availability.

Averaged over irrigation treatments, the ET of N_{120} (319 mm) and N_{60} (308 mm), and N_{30} (294 mm) and N_0 (285 mm) were statistically at par for the year 2011-12. Similarly, in the year 2012-13 all the four N treatments were statistically at par with respect to ET. Pooled over the years, N_{120} treatment (360 mm) registered 3, 7 and 10 per cent higher ET compared to N_{60} (349 mm), N_{30} (335 mm) and N_0 (328 mm), respectively. The higher ET at higher N fertilization could be due to better crop and root growth resulting from higher interception of incoming radiation and hence higher uptake of soil moisture. Caviglia and Sadras (2001), Karam *et al.* (2009) and Pradhan *et al.* (2014a) also observed higher ET with increased N fertilization in spite of reducing evaporation from soil due to better canopy coverage. The interaction effect of irrigation and N was significant with respect to seasonal ET of wheat. This is in agreement to the findings that irrigation and N have synergistic effect on ET of wheat as reported by Arora *et al.* (2007) and Karam *et al.* (2009). Averaged over the years, the highest seasonal ET registered in I_5N_{120} treatment (467 mm) was at par with I_5N_{60}, I_5N_{30} and I_5N_0 treatments.

Table 2. Seasonal evapotranspiration (ET) and grain protein content of wheat as influenced by irrigation and nitrogen levels

Treatments	ET (mm)			Grain protein content (%)		
	2011-12	2012-13	Pooled	2011-12	2012-13	Pooled
			Irrigation			
I_0	150d[#]	250d	200d	10.41a	12.08a	11.25a
I_2	272c	371c	322c	10.66a	10.62a	10.64b
I_3	354b	449b	401b	10.15a	10.95a	10.55b
I_5	430a	471a	451a	9.98a	11.19a	10.58b
			Nitrogen			
N_0	285b	372a	328c	9.64c	10.07c	9.86b
N_{30}	294b	377a	335bc	10.04bc	10.42c	10.23b
N_{60}	308a	391a	349ab	10.53ab	11.30b	10.91a
N_{120}	319a	401a	360a	10.99a	13.05a	12.02a
			Irrigation × Nitrogen			
I_0N_0	136h	237d	186g	9.93bcd	10.30e	10.12efg
I_0N_{30}	141gh	241d	191g	10.53abcd	10.79de	10.66def
I_0N_{60}	158gh	259d	209g	10.57abc	12.43bc	11.50bcd
I_0N_{120}	163g	262d	212g	10.60abc	14.81a	12.71a
I_2N_0	246f	353c	299f	10.01bcd	9.78e	9.90fg
I_2N_{30}	270ef	366c	318ef	9.77bcd	10.03e	9.90fg
I_2N_{60}	274e	371c	323ef	11.17ab	10.50de	10.83cde
I_2N_{120}	300d	393bc	346e	11.70a	12.19bc	11.94ab
I_3N_0	347c	443ab	395d	9.52cd	9.93e	9.73g
I_3N_{30}	347c	445ab	396d	9.93bcd	10.34e	10.14efg
I_3N_{60}	352c	448ab	400cd	10.06bcd	10.78de	10.42efg
I_3N_{120}	369c	459ab	414bcd	11.07ab	12.74b	11.90ab
I_5N_0	413b	453ab	433abc	9.10d	10.26e	9.68g
I_5N_{30}	416b	457ab	437ab	9.93bcd	10.52de	10.23efg
I_5N_{60}	446a	486a	466a	10.30abcd	11.49cd	10.89cde
I_5N_{120}	446a	488a	467a	10.60abc	12.47bc	11.54bc

[#] Numbers followed by same letter are not significantly different at *$P<0.05$* as per DMRT.

Yield-evapotranspiration function

The evapotranspiration production function (ETPF), the relation between ET and wheat grain yield for 2011-12 and 2012-13 is shown in fig. 2. It showed a linear and significant relationship between ET and wheat grain yield. Steiner *et al.* (1985), Zhang and Owesis (1999), Hati *et al.* (2001), Bandyopadhyay *et al.* (2010) and Pradhan *et al.* (2014a) also observed linear relationship between wheat grain yield and ET. There was considerable scatter between wheat grain yield and ET data which probably resulted from variation in the rainfall amount and distribution among the growing seasons (Table 1) as also observed by Hati *et al.* (2001) and Karam *et al.* (2009). The ETPF shows that about 78-89% variation in wheat grain yield could be explained by variation in ET (Fig. 2). The slope of ETPF and the marginal water use efficiency (MWUE) varied from 10 to 15. It indicated that with increase in ET by 1 mm, grain yield of wheat increased by 10-15 kg ha^{-1}. The slope of ETPF for the year 2011-2012 (I_5) was higher than that for 2012-13 (I_0), which indicated that the input water was used more efficiently during 2011-12 compared to 2012-13. The intercept of ETPF was less than zero for both the years (varied from -298 in 2011-12 to -1299 in 2012-13) indicating that no yield occurs below a certain threshold of ET.

Yield response factor (Ky)

The highest wheat grain yield (Ym) was 5700 kg ha^{-1} in 2011-12 and 3336 kg ha^{-1} in 2012-13 under I_5 treatment. The corresponding maximum evapotranspiration (ETm) totals were 430 mm and 471 mm, respectively. The relation between relative yield decrease (1 - Ya/Ym) and corresponding evapotranspiration deficit (1 - ETa/ETm) combined for both the years of study is shown in fig. 3. The slope of the regression (Ky) is 1.03 with coefficient of determination (R^2) of 0.85. The relationship was statistically significant at the level of $P<0.01$. The Ky value was greater than 1, which indicates that wheat crop is highly sensitive to water stress and will result in proportional yield reduction with increase in water stress. The Ky value of wheat of the present experiment is in agreement with the Ky value (>1) presented by Doorenbos and Kassam (1979).

Root study

The vertical distribution of roots at flowering stage up to the depth of 60 cm in the form of root length density (RLD) for irrigation and N treatments for both the years are presented in fig. 4. Irrespective of the treatments, the maximum RLD of wheat was observed in the 0-15 cm soil layer and it decreased with increase in depth. The vertical distribution of root showed typical conical shape which is consistent with the data reported for wheat (Sato *et al.* 2006; Izzi *et al.* 2008). The effect of irrigation and N on RLD of wheat was observed only in 0-15 and 15-30 cm soil layers but not beyond this depth (Fig. 4). The RLD of wheat showed increasing trend with the increase in irrigation and N levels. Averaged over the years and N treatments, I_5 registered 5, 20 and 29 per cent and 7, 17 and 82 per cent higher RLD than I_3, I_2 and I_0 treatments in 0-15 and 15-30 cm soil layers, respectively. The higher root growth under higher level of irrigation could be attributed to the increased level of soil water content, as also reported by Xue *et al.* (2003), Zhang *et al.* (2004), Bandyopadhyay *et al.* (2010) and Wang *et al.* (2014). Averaged over years and irrigation, N_{120} treatment registered 1, 8 and 52 per cent and 2, 10 and 65 per cent higher RLD than N_{60}, N_{30} and N_0 treatments in 0-15 cm and 15-30 cm soil layers, respectively. Increased root growth with

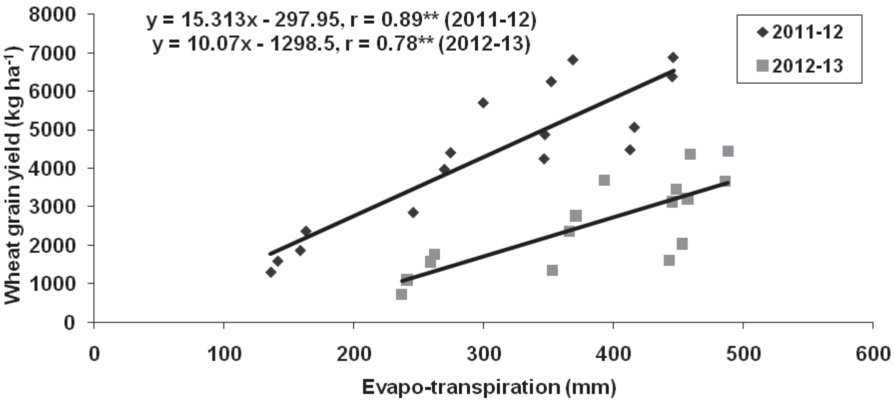


Fig. 2. Relationship between seasonal evapotranspiration and wheat grain yield (2011-12 and 2012-13)

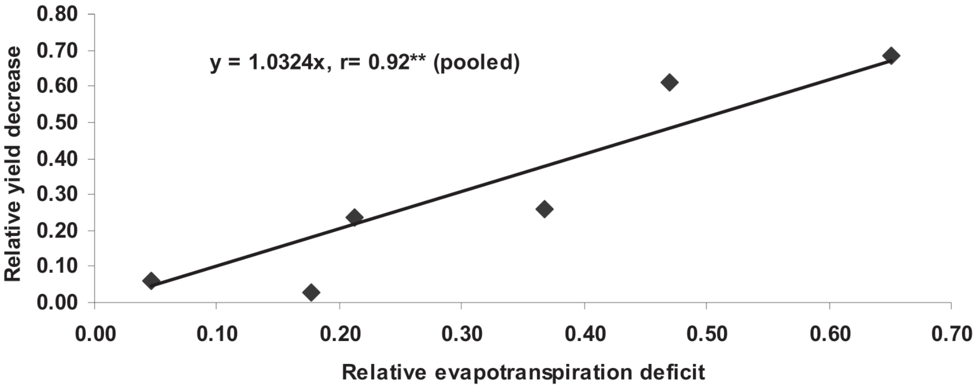


Fig. 3. Relationship between relative evapotranspiration deficit and relative yield decrease of wheat

increasing N levels have also been reported by Chakraborthy *et al.* (2010) for wheat in an Inceptisol.

Grain and aboveground biomass

The grain yield varied from 1313 (I_0N_0) to 6875 kg ha^{-1} (I_5N_{120}) with a mean value of 4318 kg ha^{-1} during 2011-12 and from 741 (I_0N_0) to 4431 kg ha^{-1} (I_5N_{120}) with a mean value of 2579 kg ha^{-1} during 2012-13 (Table 3). Similarly, aboveground biomass yield of wheat varied from 4102 (I_0N_0) to 18581 kg ha^{-1} (I_5N_{120}) with a mean value of 11298 kg ha^{-1} during 2011-12 and 3250 (I_5N_0) to 13750 kg ha^{-1} (I_5N_{120}) with a mean value of 9234 kg ha^{-1} in 2012-13. Significantly lower grain and aboveground biomass was recorded in 2012-13 compared to 2011-12, which could be attributed to aeration stress that occurred during booting and flowering period in 2012-13 due to excessive water input (rainfall + irrigation).

During 2011-12, averaged over N levels, significantly higher grain yield was observed in I_3 treatment (5547 kg ha^{-1}) compared to I_2 (4235 kg ha^{-1}) and I_0 (1791 kg ha^{-1}). However, I_3 and I_5 treatments (5700 kg ha^{-1}) were statistically at par (Table 3). But the aboveground biomass of wheat was the highest in I_5 treatment followed by I_3, I_2 and I_0. In 2012-13, I_2 treatment registered significantly higher grain yield (2543 kg ha^{-1}) compared to I_0 (1299 kg ha^{-1}), and I_2, I_3 (3138 kg ha^{-1}) and I_5 (3336 kg ha^{-1}) were statistically at par. The aboveground biomass of wheat during 2012-13 followed trend similar to grain yield. Averaged over the years, I_5 treatment registered 4, 33 and 192 per cent higher grain yield compared to I_3, I_2 and I_0, respectively. Similarly, averaged over the years, I_5 treatment registered 7, 27 and 120 per cent higher aboveground biomass compared to I_3, I_2 and I_0, respectively. The higher grain and aboveground biomass yield of wheat with increasing levels of irrigation may be attributed to better water and nutrient availability, which gave rise to better plant growth and hence yield.

The grain and aboveground biomass yield of wheat increased significantly with increase in N levels, the highest being observed in N_{120} followed by N_{60}, N_{30} and N_0 treatments in both the years (Table 3). Averaged over the years and irrigation levels, N_{120} registered 19, 42 and 93 per cent higher grain yield compared to the N_{60}, N_{30} and N_0, respectively. Similarly, averaged over the years, N_{120} treatment registered 18, 38 and 95 per cent higher aboveground biomass compared to N_{60}, N_{30} and N_0, respectively. The increased grain and biomass yield of wheat with increasing N levels could be attributed to increased leaf area index (LAI), green spikes area, and crop duration with greenness (not studied here). The interaction effect of irrigation and N on wheat grain and biomass yield was significant during both the years. Averaged over the years, the highest grain yield (5653 kg ha^{-1}) and aboveground biomass yield (16166 kg ha^{-1}) were recorded in I_5N_{120}, which were statistically at par with I_3N_{120}.

Grain protein content

The grain protein content of wheat varied from 9.10% (I_5N_0) to 11.70% (I_2N_{120}) with a mean value of 10.30% during 2011-12 and 9.80% (I_0N_0) to 14.80% (I_0N_{120}) with a mean value of 11.20% during 2012-13 (Table 4). The significantly lower (8%) grain protein content during 2011-12 than in 2012-13 could be attributed to N dilution that resulted from significantly higher yield in the first year. Terman *et al.* (1969) also observed significant inverse yield-protein relationship in wheat grain of winter wheat. Grain protein content was not influenced significantly by the irrigation levels in both the years. Averaged over

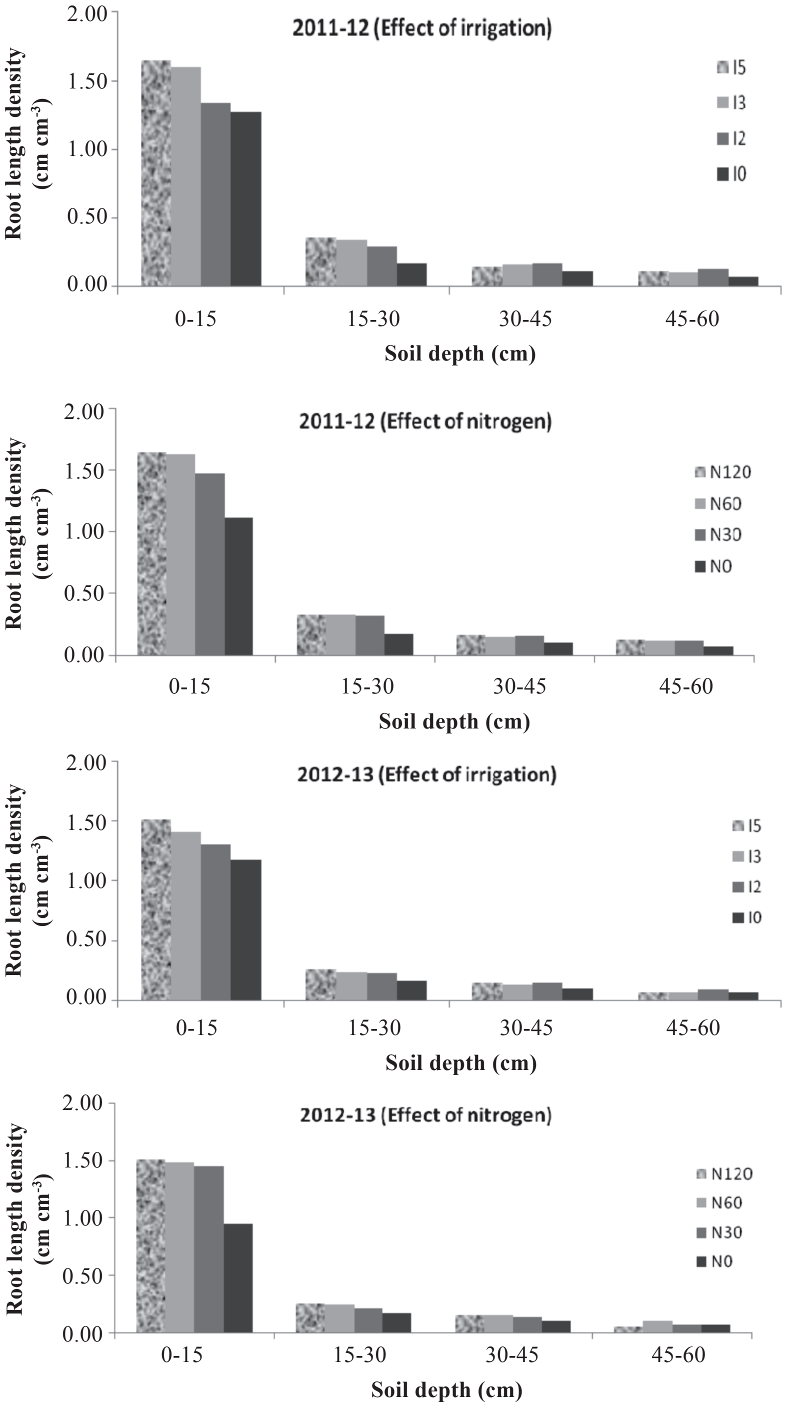


Fig. 4. Root length density of wheat under various irrigation and nitrogen treatments for the year 2011-12 and 2012-13

the years and nitrogen levels, I_0 registered 6% higher grain protein content than other irrigation treatments. Pradhan *et al.* (2012) has also reported no significant variation in wheat grain protein content due to irrigation at different levels of IW/CPE (irrigation water to cumulative pan evaporation). However, N levels had significant effect on wheat grain protein content. In the year 2011-12, averaged over irrigation levels, significantly highest grain protein content was observed in N_{120} (10.99%) and lowest in N_0 (9.64%). The N_{120} and N_{60}, N_{60} and N_{30} and N_{30} and N_0 treatments were statistically at par with respect to the grain protein content. Similarly during 2012-13, averaged over irrigation levels, the highest grain

Table 3. Grain yield (kg ha^{-1}) and aboveground biomass (kg ha^{-1}) of wheat

Treatments	Grain yield (kg ha^{-1})			Aboveground biomass (kg ha^{-1})		
	2011-12	2012-13	Pooled	2011-12	2012-13	Pooled
			Irrigation			
I_0	1791c[#]	1299b	1545c	5442d	6313b	5877c
I_2	4235b	2543a	3389b	10467c	9833a	10150b
I_3	5547a	3138a	4343a	14045b	10188a	12116a
I_5	5700a	3336a	4518a	15237a	10604a	12920a
			Nitrogen			
N_0	3227d	1441d	2334d	8474d	5188d	6831d
N_{30}	3879c	2451c	3165c	10316c	8917c	9616c
N_{60}	4727b	2865b	3796b	12135b	10500b	11317b
N_{120}	5441a	3559a	4500a	14266a	12333a	13300a
			Irrigation × Nitrogen			
I_0N_0	1313h	741h	1027h	4102g	3250k	3676i
I_0N_{30}	1600gh	1107gh	1354gh	5000fg	6250ij	5625h
I_0N_{60}	1875gh	1580fg	1728fg	5682fg	7500hi	6591gh
I_0N_{120}	2375fg	1767efg	2071f	6985f	8250gh	7618fg
I_2N_0	2858f	1363fgh	2111f	6806f	5333j	6070h
I_2N_{30}	3975e	2359de	3167de	10743e	9333fg	10038de
I_2N_{60}	4406de	2769cd	3588cd	10747e	11333cd	11040cd
I_2N_{120}	5700bc	3680b	4690b	13571cd	13333ab	13452b
I_3N_0	4250de	1619fg	2935e	11184de	5000j	8092f
I_3N_{30}	4875cde	3127bc	4001c	12188de	9750ef	10969cd
I_3N_{60}	6250ab	3449bc	4850b	14881bc	12000bc	13441b
I_3N_{120}	6813a	4358a	5585a	17928a	14000a	15964a
I_5N_0	4485de	2043ef	3264de	11803de	7167hi	9485e
I_5N_{30}	5067cd	3210bc	4138c	13334cde	10333def	11834c
I_5N_{60}	6375ab	3660b	5018b	17230ab	11167cde	14198b
I_5N_{120}	6875a	4431a	5653a	18581a	13750a	16166a

[#] Numbers followed by same letter are not significantly different at $P<0.05$ as per DMRT.

protein content was observed in N_{120} (13.05%) and lowest in N_0 treatment (10.07%), but only N_{30} and N_0 treatments were statistically at par. Pooled over the years, N_{120} registered 10, 17 and 22 per cent higher grain protein content compared to N_{60}, N_{30} and N_0 treatments, respectively. Several other workers have also reported increased levels of wheat grain protein content at higher levels of N (Gauer *et al.* 1992; Li-Hong *et al.* 2007). The interaction effect of irrigation and N on wheat grain protein content was significant during both the years. Averaged over the years, the highest grain protein content was recorded in I_0N_{120} (12.71%), which was statistically at par with I_2N_{120} and I_3N_{120} treatments.

Water and nitrogen use efficiency

The water use efficiency (WUE) of wheat varied from 9.67 (I_0N_0) to 19.06 kg ha^{-1} mm^{-1} (I_1N_3) with a mean value of 14.03 kg ha^{-1} mm^{-1} for the year 2011-12 and from 3.13 (I_0N_0) to 9.46 kg ha^{-1} mm^{-1} (I_2N_3) with a mean value of 6.50 kg ha^{-1} mm^{-1} during 2012-13 (Table 4). The significant decrease in WUE during 2011-12 compared to 2012-13 was mainly due to decrease in grain yield rather than increase in ET for the year 2012-13, which is evident from better correlation between grain yield and WUE (r = 0.71 and 0.91 for the year 2011-12 and 2012-13, respectively) than between ET and WUE (r = 0.33 and 0.48 for the year 2011-2012 and 2012-13, respectively). In 2011-12, averaged over N levels, I_3 treatment registered significantly higher WUE (15.66 kg ha^{-1} mm^{-1}) compared to I_0 (11.87 kg ha^{-1} mm^{-1}) and I_5 (13.19 kg ha^{-1} mm^{-1}) treatments. I_3 and I_2 as well as I_0 and I_5 treatments were statistically at par with respect to WUE. However, in 2012-13, WUE was not affected by irrigation treatments. Pooled over the years, I_0 treatment registered 23, 25 and 16 per cent lower WUE compared to the I_2, I_3 and I_5 treatments, respectively. Many other workers have also reported decreased or non-significant change in WUE at higher level of irrigation due to relatively greater expense of water by ET than the corresponding increase in grain yield (Gajri *et al.* 1993; Hati *et al.* 2001; Pandey *et al.* 2001; Jat *et al.* 2008; Pradhan *et al.* 2014a).

Table 4. Water use efficiency (WUE, kg ha^{-1} mm^{-1}) and partial factor productivity of nitrogen (PFP$_N$, kg grain kg^{-1} N applied) of wheat

Treatments	WUE (kg ha^{-1} mm^{-1})			PFP$_N$ (kg grain kg^{-1} N applied)		
	2011-12	2012-13	Pooled	2011-12	2012-13	Pooled
			Irrigation			
I_0	11.87b#	5.20a	8.53b	35c	26b	30c
I_2	15.38a	6.75a	11.07a	85b	52ab	68b
I_3	15.66a	6.99a	11.33a	108a	66a	87a
I_5	13.19b	7.08a	10.13a	111a	68a	90a
			Nitrogen			
N_0	11.13d	3.81d	7.47d	-	-	-
N_{30}	13.07c	6.28c	9.68c	129a	82a	106a
N_{60}	15.00b	7.24b	11.12b	79b	48b	63b
N_{120}	16.91a	8.68a	12.80a	45c	30c	38c
			Irrigation × Nitrogen			
I_0N_0	9.70h	3.13e	6.40h			
I_0N_{30}	11.33fgh	4.70de	8.01gh	53de	37de	45de
I_0N_{60}	11.87fgh	6.13cd	9.01fg	31ef	26ef	29fg
I_0N_{120}	14.60cdef	6.83c	10.71def	20f	15f	17g
I_2N_0	11.70fgh	3.88e	7.78gh			
I_2N_{30}	14.70cdef	6.29cd	10.51def	133b	79b	106b
I_2N_{60}	16.07abcd	7.49abc	11.78cd	73d	46cd	60d
I_2N_{120}	19.03a	9.36a	14.21a	48de	31def	39ef
I_3N_0	12.27efgh	3.66e	7.97gh			
I_3N_{30}	14.07defg	7.11bc	10.59def	163a	104a	133a
I_3N_{60}	17.70abc	7.71abc	12.73abc	104c	57c	81c
I_3N_{120}	18.57ab	9.46a	14.01ab	57de	36de	47de
I_5N_0	10.90gh	4.56de	7.73gh			
I_5N_{30}	12.17efgh	7.04bc	9.59efg	169a	107a	138a
I_5N_{60}	14.30defg	7.62abc	10.96cde	106c	61c	84c
I_5N_{120}	15.40bcde	9.09ab	12.26bcd	57de	37de	47de

#Numbers followed by same letter are not significantly different at $p<0.05$ as per DMRT.

However, the water use efficiency increased significantly with increase in N levels from 0 to 120 kg ha^{-1} for both the years. Averaged over the years and irrigation levels, N_{120} treatment registered 15, 32 and 71 per cent higher WUE compared to N_{60}, N_{30} and N_0 treatments, respectively. The higher WUE at higher N doses was mainly due to higher grain yield of crops with similar water use/ET at higher N doses (Pandey *et al.* 2001; Pradhan *et al.* 2014a). The interaction effect of irrigation and N on WUE of wheat was significant during both the years. Averaged over the years, the highest WUE was recorded in I_2N_{120} treatment (14.21 kg ha^{-1} mm^{-1}), which was statistically at par with I_3N_{120}.

The N use efficiency in the form of partial factor productivity of N (PFP$_N$) varied from 20 (I_0N_{120}) to 169 kg of grain kg^{-1} of N applied (I_5N_{30}) with a mean value of 84 kg of grain kg^{-1} of N applied for 2011-12. During the second year it varied from 15 (I_0N_{120}) to 107 kg of grain kg^{-1} of N applied (I_5N_{30}) with a mean value of 53 kg of grain kg^{-1} of N applied. The significant decrease in PFP$_N$ in 2012-13 compared to 2011-12 may be attributed to significant decrease in wheat grain yield in the second year. The PFP$_N$ increased with increase in irrigation levels in both the years. In 2011-12, averaged over N levels, I_5 treatment showed significantly higher PFP$_N$ compared to I_2 and I_0 whereas I_5 and I_3 treatments were statistically at par with respect to PFP$_N$. However, in 2012-13, I_5 showed significantly higher PFP$_N$ compared to I_0 and I_5, I_3 and I_2 treatments were at par (Table 4). Averaged over the years, I_5 registered 3, 32 and 200 per cent higher PFP$_N$ compared to I_3, I_2 and I_0, respectively. Gajri *et al.* (1993) and Jat *et al.* (2008) have also observed higher NUE at higher levels of irrigation in wheat, which they attributed to the better N mineralization leading to better plant uptake of N and hence growth and yield. Averaged over the irrigation levels, PFP$_N$ decreased significantly with increase in N levels from 30 to 120 kg N ha^{-1} during both the years (Table 4). This may be attributed to losses of N at higher levels of application and to the fact that yield of wheat did not increase in the same proportion as N application. Similar results have also been reported by many other workers for wheat (Gauer *et al.* 1992; Gajri *et al.* 1993; Chakraborthy *et al.* 2010; Pradhan *et al.* 2014a). The interaction of irrigation and N on NUE was found significant during both the years, which supported earlier findings of Gajri *et al.* (1993) and Pradhan *et al.* (2014a). The highest NUE was observed in I_5N_{30} treatments for both the years. Treatment I_3N_{30} was at par with I_5N_{30} in this respect. Averaged over the years, the NUE for wheat in I_5N_{30} treatment was 138 kg grain kg^{-1} N applied and for I_3N_{30} treatment, it was 133 kg grain kg^{-1} N applied.

Conclusions

The study inferred that wheat (cv. HD 2932) can be grown with three irrigations (CRI, tillering and flowering stages) and 120 kg N ha^{-1} for optimum yield, grain protein content and water use efficiency in the semi-arid region of Delhi.

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