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Optimizing water and nitrogen use for maize production under semiarid conditions

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Abstract: Water and nitrogen are among the most important crop inputs for optimum production of maize (*Zea mays* L.). A comprehensive experiment was conducted during 2009 and 2010 under the semiarid conditions of Pakistan to evaluate the effects of water and N applications on the growth and yield of irrigated maize. The objective was to formulate water and N best management practices (BMPs) for the above conditions. Three irrigation regimes (525, 450, and 375 mm ha^{-1}) with 5 N rates (0, 75, 150, 225, and 300 kg ha^{-1}) were tested using a split plot with a randomized complete block design. The results revealed that the irrigation and N treatments significantly affected growth and development of the crop plants. Photosynthesis and transpiration rates were influenced by the applied nutrients. The N application at 225 kg ha^{-1} resulted in maximum values for photosynthesis (26.90 and 27.63 µmol m^{-2} s^{-1} during 2009 and 2010, respectively) and transpiration (5.23 and 5.43 m mol m^{-2} s^{-1} during 2009 and 2010, respectively). The highest values for leaf area index (4.93) and grain yield (8.40 t ha^{-1}) were also recorded at this N treatment during both growing seasons. On the other hand, the mean crop growth rate (19.23 g m^{-2} day^{-1}) and biological yield (16.22 t ha^{-1}) were achieved with the 300 kg N ha^{-1} treatments in 2009 and 2010. Nitrogen use efficiency (NUE) was optimum at 75 kg N ha^{-1} during both seasons. The highest water use efficiency (WUE) (16.48 and 18.64 kg ha^{-1} mm^{-1} during 2009 and 2010, respectively) was achieved by application of 225 kg N ha^{-1} with an irrigation water depth of 525 mm during both growing seasons. Water stress at the vegetative stage reduced the grain yield by 12.2%, whereas the same treatment at the grain filling stage reduced the grain yield by 22.6%. In the semiarid environment of Pakistan, the application of water at 525 mm ha^{-1} with 225 kg N ha^{-1} gave the optimum production of the irrigated maize tested in this experiment. These crop inputs may be considered as water and N BMPs for this region or for those with similar agricultural and environmental conditions. Agricultural inputs based on these BMPs may result in similar NUE and WUE values.

Key words: Crop growth, maize yield, nitrogen use efficiency, photosynthesis, transpiration, water use efficiency

Introduction

Agricultural best management practices (BMPs) are effective, practical, and structural or nonstructural methods adopted to optimize crop production and minimize environmental impacts (Abbas and Fares 2009). The formulation of water and nitrogen BMPs is needed to ensure food productivity for the increasing world population and to address the growing concerns regarding the adverse environmental impacts of agricultural activities.

Maize production responds positively to supplemental irrigation water and applied N to the

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optimum level (Liu and Zhang 2007; Gül et al. 2008; Gheysari et al. 2009). Both water and N are the main abiotic factors that limit the yield of maize worldwide (Araus et al. 2002). Water deficits at any growth stage reduce crop productivity (Paudyal et al. 2001) by reducing leaf area (Pandey et al. 2000), shoot growth (Stone et al. 2001), plant height (Soler et al. 2007), and grain yield (Payero et al. 2006). Similarly, heavy crop losses worldwide occur due to water deficiency. Maize yield decreases when the crop is subjected to water stress and high doses of N (Grant et al. 2002; Moser et al. 2006). Hence, there is a close relationship between soil moisture and N availability for plant uptake (Hussaini et al. 2008; Aynehband et al. 2011). High evapotranspiration rates in crops influenced by regional climatic conditions can be an important crop production factor and an increase in evapotranspiration may lead to soil moisture deficit (Shukla and Mintz 1982; Easterling and Karl 2001; Hussein et al. 2011). The literature reveals that photosynthetically active radiation and water potential frequency are positively correlated with grain yield.

Nitrogen deficiency obviously reduces light interception by decreasing the leaf area index (LAI) and hence results in a lower crop yield (Uhart and Andrade 1995; Glamoclija et al. 2011). However, maize is more tolerant of a limited N supply during its early vegetative phase compared to the later stages (McCullough et al. 1994; Islam et al. 2010). There is a positive relationship between photosynthetic rate and the yield formation processes of various maize hybrids (Ding et al. 2005).

It has been reported that the commonly recommended dose of 200 kg N ha^{-1} is not optimal for maize in semiarid environments (Khaliq et al. 2009; Hammad et al. 2011b). Application of a sufficient dose of N at the proper time is considered to be the single most significant factor in improving crop productivity (Magdoff 1991). Judicious N management optimizes grain yield and reduces N leaching. A balance between the requirements and application of irrigation water and N is important to formulate water and N BMPs, especially for semiarid regions. The goal of developing BMPs is to achieve a balance between crop production and environmental protection (Abbas and Fares 2009).

The establishment of water and N BMPs for maize requires determining the optimal doses of these crop inputs for optimum productivity of the crop (Li et al. 2010). Therefore, the present experiment was conducted to achieve this objective by studying the physiological and agronomic characteristics of maize in the semiarid environment of Pakistan.

Materials and methods

Experiment site

This experiment was conducted at the Agronomic Research Farm of the University of Agriculture in Faisalabad (31°25′N, 73°04′E) during the autumns of 2009 and 2010. The daily meteorological data for both growing seasons are presented in Figure 1.

Soil analysis

Composite soil samples were taken from a depth of 25 cm at the experiment site prior to seeding. The samples were analyzed for major physical and chemical soil properties following standard procedures (Table 1).

Experimental design and treatments

This experiment was conducted using a split plot with a randomized complete block design where the treatments were replicated in triplicate. A total of 45 experimental plots measuring 21 m^2 (3 × 7 m) each were prepared to accommodate 4 rows of maize in each plot 0.75 m apart with a distance of 0.20 m between plants.

Irrigation water was applied at various crop growth stages as described by Ritchie and Hanway (1993). Phenological observations of 10 tagged plants per plot were made on a daily basis in order to distinguish crop growth stages. Canal irrigation water with electrical conductivity of 0.58 mS cm^{-1} and 371 g m^{-3} total soluble salt was applied using a surface irrigation method. The depth of the irrigation water was controlled using a cut-throat flume that was installed at the main water channel originating from an irrigation canal as per water management practices of irrigated agriculture in Pakistan. The 3 irrigation schedules were:

I_1 (in the V4, V8, V14, V18, VT, R1, and R3 stages),
I_2 (in the V6, V12, VT, R1, and R3 stages), and
I_3 (in the V4, V8, V14, V18, VT, and R3 stages),

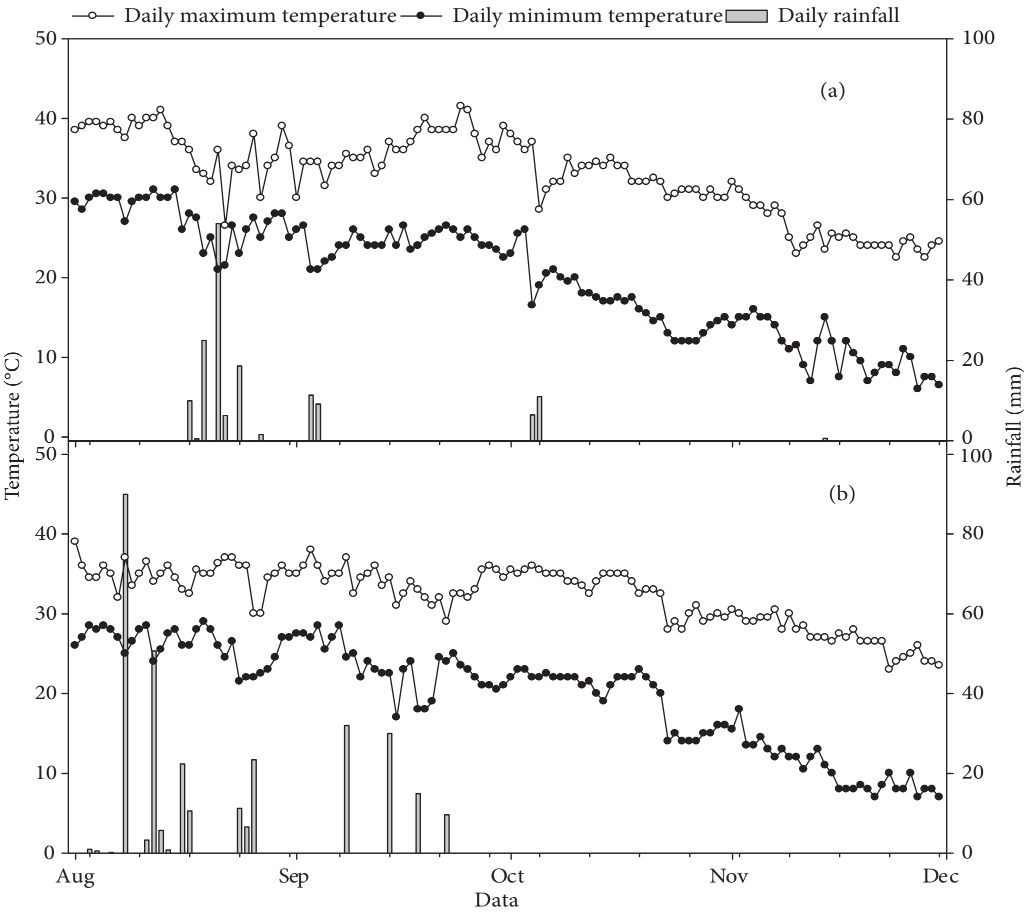

Figure 1. Daily meteorological data of the experiment site during a) the 2009 and b) the 2010 growing seasons.

where V is a vegetative stage, R is a reproductive stage, T is a tasseling stage, R1 is a silking stage, and R3 is a blister stage. Irrigation treatments were practiced in the main plots with an application depth of 75 mm. The following formula was used to calculate irrigation depth:

$$Q = \frac{(axd)}{t}$$

where Q is the discharge measured through the cut-throat flume ($m^3 s^{-1}$), A is the area to be irrigated (m^2), d is the depth of the water applied (m), and t is the time to irrigate a given area in seconds.

Five N treatments, named N_1, N_2, N_3, N_4, and N_5 for 0, 75, 150, 225, and 300 kg N ha^{-1}, respectively, were kept in subplots. Urea fertilizer (46% N) was used as the source of N.

Crop husbandry

A maize hybrid, Pioneer 31-R-88 (FAO maturity group 700), was seeded on 1 August 2009 and 2 August 2010. This hybrid is commonly used in Pakistan's semiarid region (Khaliq et al. 2009). Phosphorus was applied at the rate of 130 kg ha^{-1} and potassium at 110 kg ha^{-1}; both fertilizers were manually applied at planting time. One-third of the N was applied at the time of sowing and the rest of the N dose was applied in 2 splits according to each treatment.

Plant thinning was done after germination to obtain a target population of 66,660 plants ha^{-1}. All other agronomic practices such as hilling, hoeing, and plant protection measures were kept the same for each treatment. Weeds were removed manually. No herbicide was applied to the crop. Hoeing was done 20 days after planting (DAP) with a hand tool. Hilling

Table 1. Selected physical and chemical properties of the soil at the experiment site.

Soil properties	**Values**	
	2009	**2010**
Clay	39%	40%
Silt	31%	32%
Sand	30%	28%
Bulk density	1.41 g cm^{-3}	1.41 g cm^{-3}
EC	1.64 dS m^{-1}	1.69 dS m^{-1}
Saturated water content	0.43 cm^3 cm^{-3}	0.44 cm^3 cm^{-3}
Field capacity	0.32 cm^3 cm^{-3}	0.33 cm^3 cm^{-3}
Permanent wilting point	0.21 cm^3 cm^{-3}	0.21 cm^3 cm^{-3}
Textural class	sandy clay loam	sandy clay loam
Organic matter	0.95%	0.97%
pH	7.45	7.43
Nitrogen	6.74 mg kg^{-1}	6.80 mg kg^{-1}
Phosphorus	7.13 mg kg^{-1}	7.20 mg kg^{-1}
Potassium	18.4 mg kg^{-1}	18.5 mg kg^{-1}

was done 40 DAP. The crop was harvested manually at physiological maturity.

Sampling

One-third of each plot was specified for plant sampling to monitor growth and development, and the remaining portions of the plots were left for harvesting. In each plot, 5 plants were randomly selected for harvest to ground level on a biweekly basis. The fresh and dry weights of the plants were determined separately by drying the subsamples in an oven (Model: WFO-600ND, Tokyo Rikakikai Co.) at 70 °C until a constant weight was reached.

A subsample of 10 g of leaf lamina was taken at 14-day intervals to calculate leaf area with a leaf area meter (CI-202, CID Bio-Science); LAI was calculated using a standard formula (Watson 1952). Similarly, crop growth rate (CGR) was calculated following the technique explained by Hunt (1978). The oven-dried samples were used for total dry matter calculations.

Transpiration and photosynthesis rates were measured at V and R stages in fully expanded third leaves of the plants using a portable photosynthesis system (LCi analyzer, LI-COR) at 0900 and 1100 hours with molar flow of air per unit of leaf area, leaf chamber water pressure of –0.33 MPa, photosynthetically active radiation of up to 900 mol m^{-2} s^{-1} at the leaf surface, and a relative humidity of 75%.

At maturity, 20 plants from a harvest area of 1.5 m × 2 m were harvested to estimate various yield components such as grain number per ear, 1000-grain weight, and yield of biological and grain components. Harvest index (HI) was calculated using a standard procedure (Hühn 1990).

$$HI = \frac{\text{Grain yield}}{\text{Biological yield}} \text{ x } 100$$

Water use efficiency (WUE) was calculated as grain yield divided by total water (evapotranspiration) consumed by the crop during the season for a specific treatment (Latiri-Souki et al. 1998) while evapotranspiration (ET) was calculated using the Decision Support System for Agrotechnology Transfer (DSSAT) model (Hoogenboom et al. 2011). Daily maximum and minimum temperatures with solar radiation (Figure 1) and soil properties of the experimental site (Table 1) were used as the DSSAT model inputs.

Nitrogen use efficiency (NUE) was calculated using agronomic efficiency of the crop for each N treatment with a standard procedure (Dobermann 2007).

$$\mathrm{NUE} = \frac{(Y - Y^{\circ})}{F}$$

where Y is grain yield (kg ha^{-1}) with applied N (kg ha^{-1}) and Y° is grain yield (kg ha^{-1}) without N, and F is the amount of N fertilizer applied (kg ha^{-1}).

Statistical analysis

The statistical analysis was conducted using SAS (SAS Institute 2004). When F-values were significant, the least significant difference (LSD) test was used for comparing treatments means. Response of yield and plant growth to N rates was evaluated using polynomial contrasts (linear, quadratic, and cubic) within the analysis of variance structures.

Results

Effect of treatments on plant growth parameters

Irrigation treatments significantly affected LAI, which gradually increased for all treatments up to 63 DAP, at which point it declined as the crop matured during both seasons (Figures 2a and 2b). Nitrogen rates also significantly influenced LAI. The highest LAI was reached in the N_4 treatments whereas the lowest LAI was observed in the N_1 treatments during both seasons (Figures 2c and 2d).

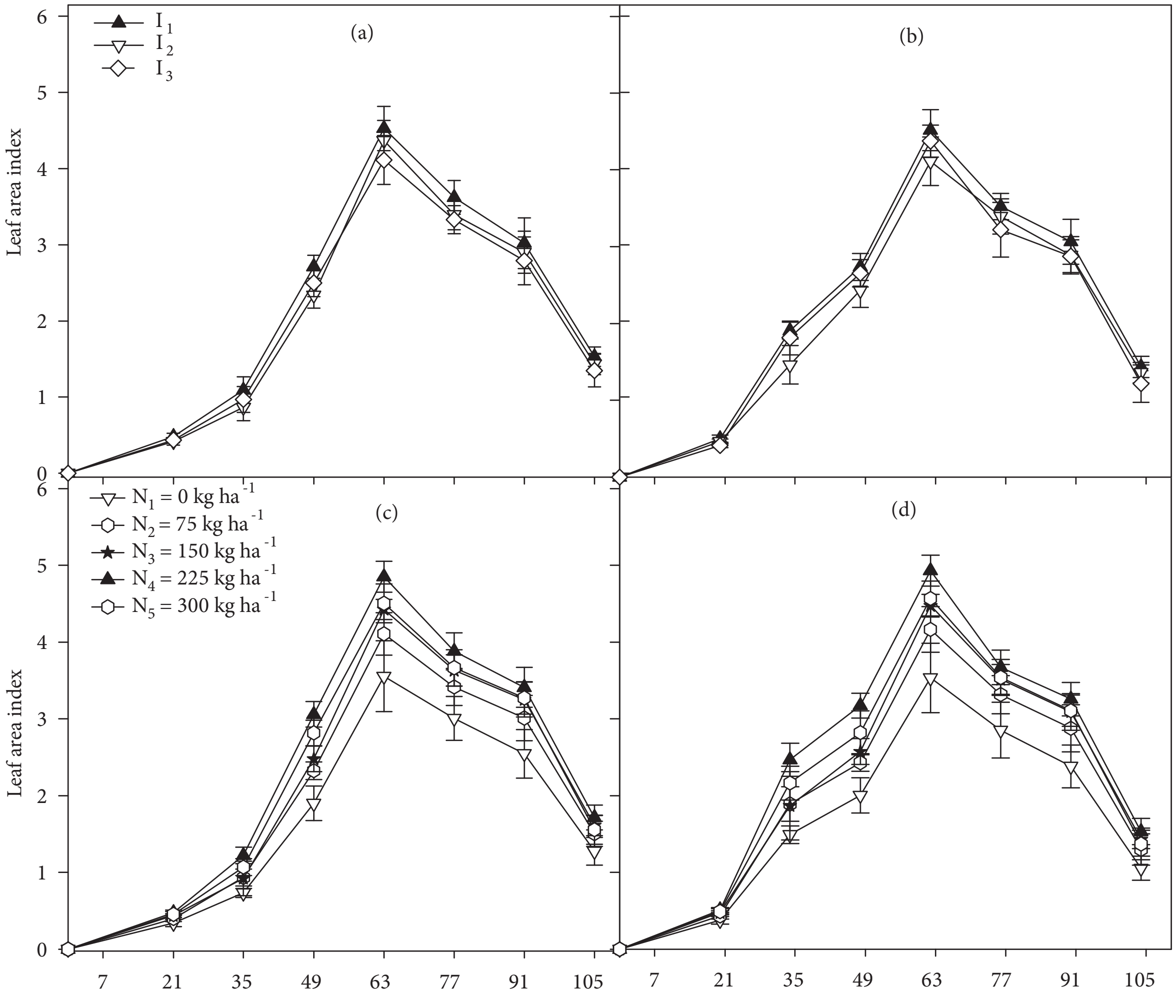

Figure 2. Change in the leaf area index of maize with time during the a) 2009 irrigation treatments, b) 2010 irrigation treatments, c) 2009 nitrogen treatments, and d) 2010 nitrogen treatments.

CGR was significantly affected by the irrigation treatments as it steadily increased up to the R1 stage and then declined. A sharp reduction in CGR was recorded in the water deficit condition (Figures 3a and 3b); in the R stage, the CGR was lower for the I_3 treatments than for the other 2 irrigation treatments. The N application significantly influenced CGR as it continuously increased up to N_5. The mean of CGR was low for the reduced N treatments (Figures 3c and 3d).

Total dry matter production (TDMP) was significantly influenced by both the irrigation and the N treatments (Figure 4). However, in the early growing stages, TDMP remained similar for all irrigation treatments (Figures 4a and 4b). This may be due to more rainfall occurring during the V stage, especially during the 2010 season (Figure 1). The lowest TDMP was observed in the I_3 treatment. TDMP increased with increasing N rates, with the highest TDMP occurring in the N_5 treatment (Figures 4c and 4d). There was a positive correlation between TDMP and mean photosynthesis and crop growth rate (Figures 5a-5d).

Physiological activities

Transpiration and photosynthesis rates in the V and R stages are presented in Table 2. In the V stage, maximum transpiration was recorded in the I_1 treatment while the lowest transpiration rate was reached in the I_2 treatment. However, in the R stage, the lowest transpiration rate was observed in the I_2

Table 2. Influence of irrigation and nitrogen treatments on the transpiration and photosynthesis of crops in their vegetative and reproductive stages during the 2009 and 2010 growing seasons.

Treatments	**----- Transpiration (m mol m^{-2} s^{-1}) -----**				**---- Photosynthesis (μmol m^{-2} s^{-1}) ----**			
	Vegetative stage		**Reproductive stage**		**Vegetative stage**		**Reproductive stage**	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
I_1	5.03 a	5.10 a	4.70 a	4.80 a	24.25 a	25.33 a	20.93 a	21.32
I_2	3.76 c	3.87 b	4.41 b	4.57 a	20.36 b	20.62 c	18.80 a	18.36
I_3	4.50 b	4.31 b	3.32 c	3.37 b	23.21 a	24.45 b	14.56 b	15.09
LSD 5%	0.31	0.60	0.22	0.35	1.448	0.52	2.51	1.12
Significance	**	**	**	*	**	**	**	*
N_1	3.48 e	3.47 d	3.23 c	3.19 c	16.57 e	17.09 e	12.94 d	12.61 d
N_2	4.03 d	4.01 cd	3.90 b	4.15 b	21.00 d	21.84 d	16.11 c	16.35 c
N_3	4.51 c	4.42 bc	4.26 b	4.41 b	23.47 c	24.27 c	19.26 b	19.61 b
N_4	5.23 a	5.43 a	5.05 a	5.21 a	26.90 a	27.63 a	21.94 a	22.20 a
N_5	4.89 b	4.79 ab	4.27 b	4.30 b	25.10 b	26.01 b	20.93 b	20.52 b
LSD 5%	0.33	0.67	0.50	0.45	1.55	0.78	1.53	1.05
Significance	**	**	**	**	**	**	**	**
Linear	**	**	**	**	**	**	**	**
Quadratic	**	NS	**	**	**	**	**	**
Cubic	*	*	*	*	NS	**	*	**
Mean	4.28	4.42	4.14	4.24	21.21	23.36	17.76	18.26
I × N	NS	NS	NS	NS	NS	*	NS	NS
CV %	7.67	15.61	12.35	10.78	7.05	3.42	8.71	5.92

Means sharing different letters in a column vary significantly at $P \leq 0.05$.

LSD = least significant difference; *, ** = significant at 5% and 1%, respectively; CV = coefficient of variation; NS = nonsignificant; I_1 = 525 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, R1, and R3 stages); I_2 = 450 mm ha^{-1} (irrigation in the V6, V12, VT, R1, and R3 stages); I_3 = 375 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, and R3 stages); N_1 = 0 kg ha^{-1}; N_2 = 75 kg ha^{-1}; N_3 = 150 kg ha^{-1}; N_4 = 225 kg ha^{-1}; and N_5 = 300 kg ha^{-1}.

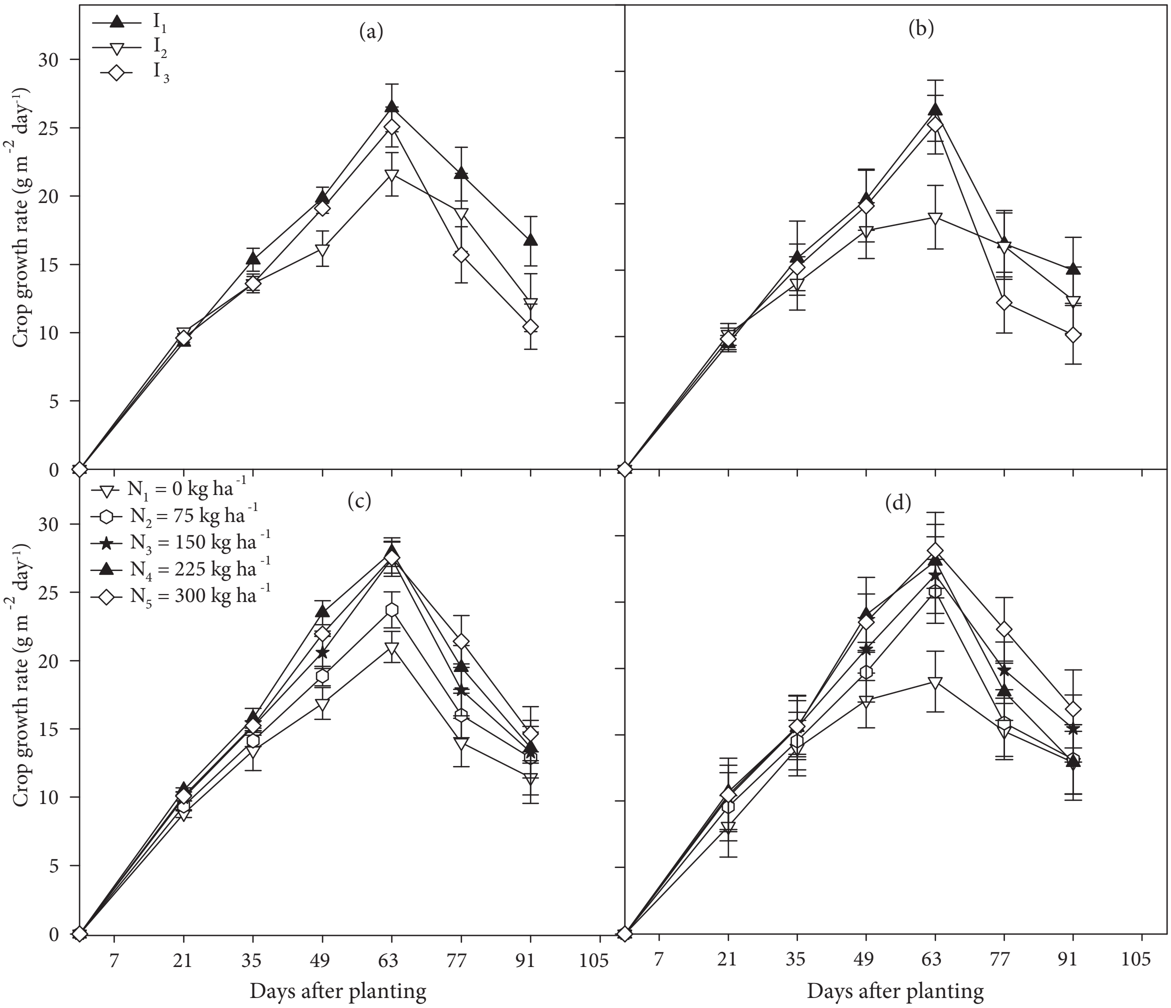

Figure 3. Change in the crop growth rate of maize with time during the a) 2009 irrigation treatments, b) 2010 irrigation treatments, c) 2009 nitrogen treatments, and d) 2010 nitrogen treatments.

treatment during both growing seasons. Nitrogen treatments significantly influenced transpiration rates during the growing seasons of 2009 and 2010. The effect of the N was cubic. In both the V and the R stages, a decline in transpiration occurred with reduction of the N dose. The maximum transpiration rates at these stages were recorded in the N_4 treatments for both years.

Photosynthesis rate (PR) was significantly affected by the irrigation treatments in both years. In general, the PR was higher in the V stage than in the R stage for all treatments during both seasons. The PR was significantly reduced by water deficit in both stages. It was significantly affected by the N rates with cubic effects. The optimum PR for the V and R stages was observed in the N_4 treatments during both years.

Effects of treatments on crop yield

The irrigations and N treatments significantly affected crop yield parameters (Table 3). Grain count per cob was significantly influenced by the irrigation treatments. During both years the maximum number of grains per cob was recorded in the I_1 treatments, whereas the lowest number of grains per cob was observed in the I_3 treatments. Nitrogen rates significantly increased the number of grains per cob with linear and quadratic effects of N for various treatments. The highest number of grains per cob was recorded in the N_4 treatments, which was statistically

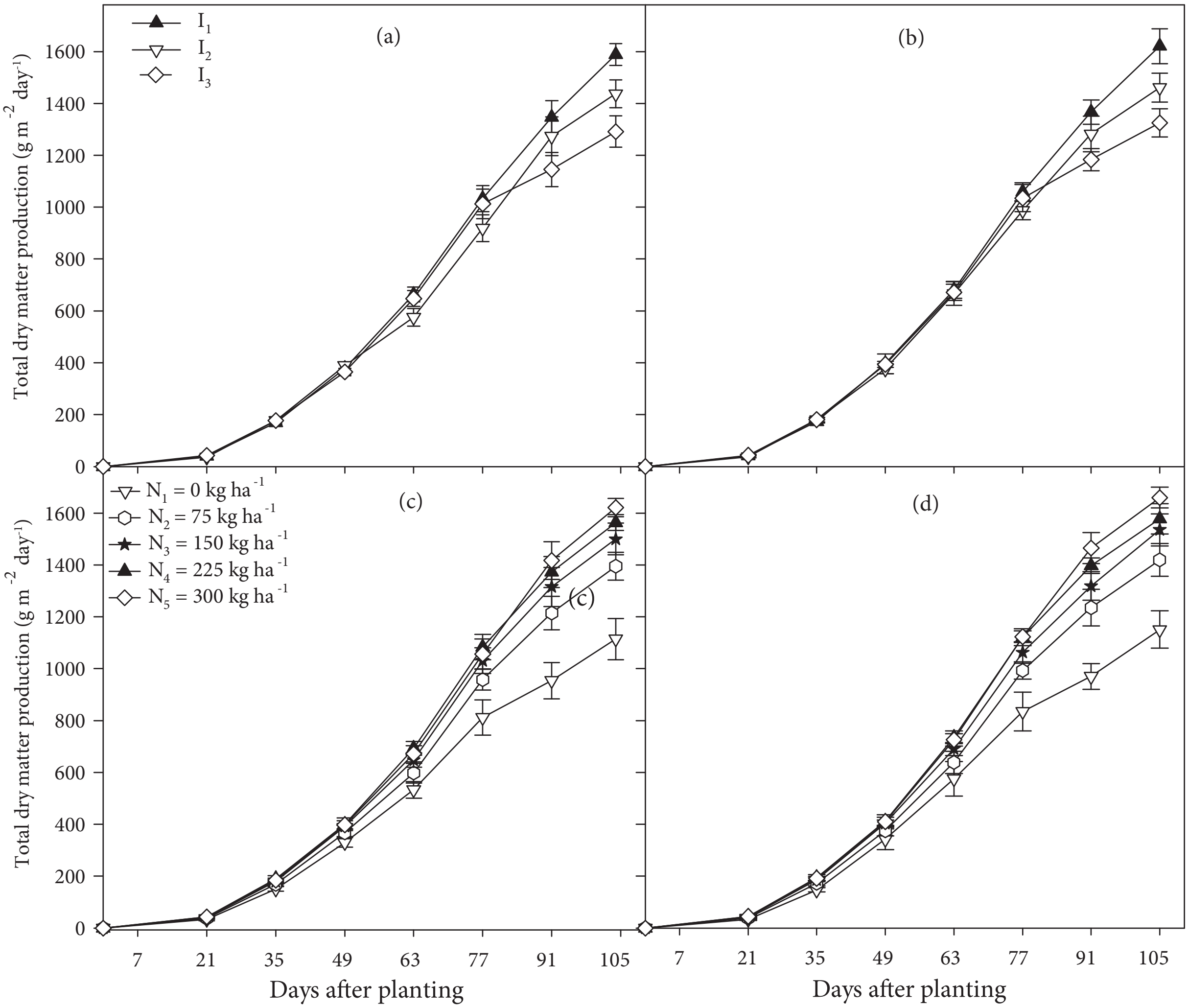

Figure 4. Change in the total dry matter production of maize with time during the a) 2009 irrigation treatments, b) 2010 irrigation treatments, c) 2009 nitrogen treatments, and d) 2010 nitrogen treatments.

similar to that in the N_5 treatments. The treatment without N fertilizer gave the lowest number of grains per cob.

The irrigation treatments significantly affected 1000-grain weight. The maximum 1000-grain weight was achieved in the I_1 treatments while water stress in the R stage (I_3) showed the statistically lowest 1000-grain weight in both years. Nitrogen rates significantly influenced 1000-grain weight (Table 3). The highest 1000-grain weight was recorded in the N_4 treatments, and there was no significant difference between the 1000-grain weights for the N_3 and the N_5 treatments during both years.

A significant interaction was observed between the irrigation and N treatments for grain yield, and the effect of N fertilizer on grain yield was quadratic during both study years (Table 3). Water stress in the V stage reduced the grain yield by 12% and 11.5% in 2009 and 2010, respectively, whereas in the R stage the grain yield was reduced by 21.6% and 22.3% in 2009 and 2010, respectively. The highest grain yield (8.28 and 8.40 t ha^{-1} in 2009 and 2010, respectively) was achieved in the I_1N_4 treatments, and in 2009 it was statistically similar to the I_1N_5 treatment. The lowest grain yield was recorded with water deficit in the R stage without nitrogenous fertilizer treatments (I_3N_1 treatments), and the yield was statistically similar to

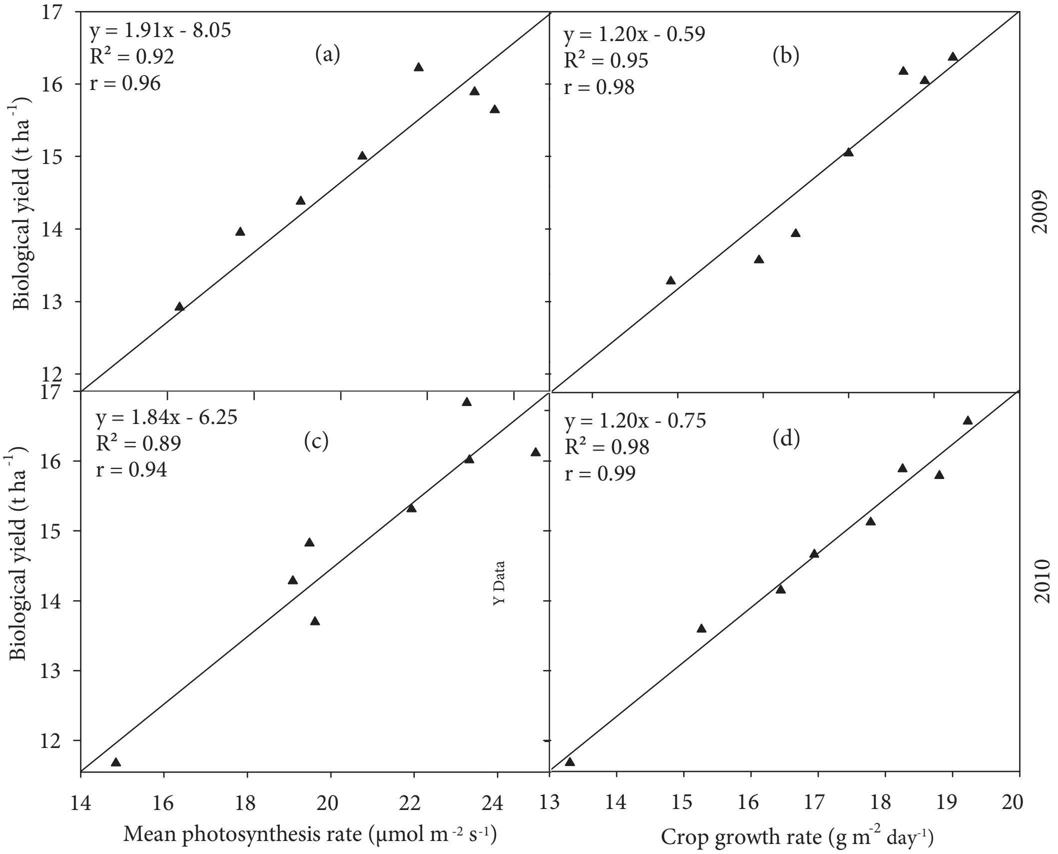

Figure 5. Relationship between biological yield and a) mean photosynthesis rate in 2009, b) mean crop growth rate in 2009, c) mean photosynthesis rate in 2010, and d) mean crop growth rate in 2010.

that for the I_2N_1 and I_1N_1 treatments in 2009. There was a strong positive correlation of grain yield with grains per cob, 1000-grain weight, and biological yield (Figure 6). The interaction of N and irrigation was significant and the effect of N was quadratic for HI during both years (Table 3). The highest HI during 2009 (46.4%) and 2010 (45.9%) was observed for the I_1N_4 interaction, and the effect was statistically similar to that for the I_2N_4 treatments during both years.

Water and nitrogen use efficiencies

Irrigation and N showed significant effects on WUE and the effect of the N was cubic during both years (Table 3). A significant interaction was observed between both factors. The highest WUE was recorded when water was applied at 530 mm ha^{-1} with 225 kg N ha^{-1} (the interaction of $I_1 \times N_4$). Water stress in the R stage with the lowest N application resulted in the lowest WUE during both years. NUE was significantly affected by both irrigation and N treatments, and the effect of the N was cubic during both years (Table 3). Consequently, a significant I × N interaction occurred at the optimum NUE recorded in the application of water at 450 mm ha^{-1} and 150 kg N ha^{-1} (the interaction of $I_2 \times N_2$).

Discussion

The effects of water and N treatments on some growth and physiological traits of irrigated maize were investigated under the semiarid conditions of Pakistan. Under favorable moisture conditions, the LAI of maize was amplified with the application of N fertilizer and declined with a decrease of N doses, as observed by Valero et al. (2005) and Zhao et al. (2005). Nitrogen affects crop production through different mechanisms. Since it accelerates formation

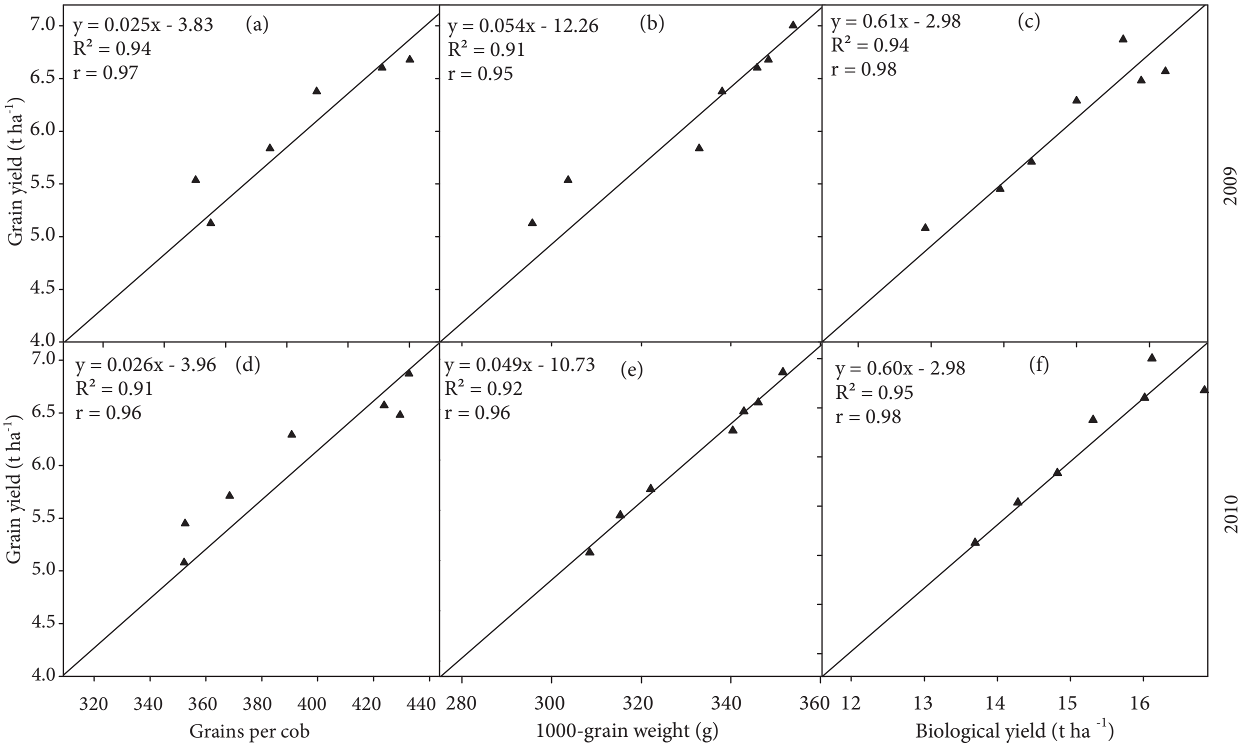

Figure 6. Relationship between grain yield and a) grain count per cob in 2009, b) 1000-grain weight in 2009, c) biological yield in 2009, d) grain count per cob in 2010, e) 1000-grain weight in 2010, and f) biological yield in 2010.

of chlorophyll, it increases cell counts and volume per leaf. The treatments affected biological yield due to an increase in biomass of the maize plants during the early parts of the growing seasons. Water stress imposed at the vegetative stage decreased leaf area (Figures 2a and 2b), but water deficit at the reproductive stage severely limited the CGR (Figures 3a and 3b), TDMP (Figures 4a and 4b), grain count per cob, and 1000-grain weight, resulting in reduced grain yield (Akçura 2011; Anjum et al. 2011; Hammad et al. 2011b). An increase in TDMP with a higher rate of N was due to better CGR and LAI values, which ultimately produced more biological yield. Nutrient stress at flowering significantly decreased CGR (Figures 3a and 3b), leading to a reduction in grain yield (Table 3). Water deficiency during the reproductive stage reduced plant growth, resulting in decreased grain yield (Çakır 2004). A nonsignificant reduction in grain yield during the vegetative stage indicates that the crop did not suffer water deficit until later in the season. Contrary to the findings of Kang et al. (2000), who reported that a water deficit during early growth stages had no significant effect on grain yield, our results showed that the grain count per ear and 1000-grain weight were more affected by water stress during the reproductive stage, as reported in the literature (e.g., Fapohunda and Hossain 1990; Pandey et al. 2000).

Since photosynthesis and transpiration occur in plant leaves, these 2 phenomena are negatively affected during water deficit conditions (Koichi et al. 2005). Higher photosynthesis and transpiration rates were recorded in the vegetative stage than in the reproductive stage (Table 2) due to a severe reduction in LAI after silking (Figure 2). Stomatal closure induced by water stress reduces both the rate of transpiration (Wu et al. 2011) and the rate of photosynthesis (Mahajan and Tuteja 2005; Farooq et al. 2009).

Nitrogen deficiency also decreased photosynthesis, which affected biological yield as demonstrated by the correlation between photosynthesis and biological yield (Figures 5a-5d). Increased application of N fertilizer is not a sound strategy for obtaining

Table 3. Effect of irrigation and nitrogen treatments on yield and yield components of maize.

Treatments	**Grain count per cob**		**1000-grain weight (g)**		**Grain yield (t ha^{-1})**		**Harvest index (%)**	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
I_1	406 a	411 a	349 a	347 a	6.48 a	6.60 a	40.21	40.66
I_2	369 b	375 b	344 a	339 a	5.71 ab	5.84 ab	39.27	39.02
I_3	352 c	355 b	314 b	313 b	5.08 b	5.13 b	39.07	37.30
LSD 5%	9	31	22	20	0.85	0.87	4.85	5.28
Significance	**		*		*	**	NS	NS
N_1	311 d	309 d	300 c	303 b	3.61 d	3.68 d	32.40 d	31.68 d
N_2	345 c	350 c	322 b	319 b	5.45 c	5.54 c	39.15 c	38.84 c
N_3	383 b	390 b	345 a	342 a	6.29 b	6.38 b	41.96 ab	41.42 ab
N_4	425 a	432 a	357 a	353 a	6.87 a	7.00 a	43.71 a	43.23 a
N_5	416 a	420 a	352 a	349 a	6.57 ab	6.70 b	40.36 bc	39.60 bc
LSD 5%	20	21	21	20	0.31	0.30	1.96	2.56
Significance	**	**	**	*	**	**	**	**
Linear	**	**	**	**	**	**	**	**
Quadratic	**	**	**	NS	**	**	**	**
Cubic	NS	NS	NS	NS	NS	NS	NS	NS
$I_1 \times N_1$	353	357	288	292	3.83 f	3.98 g	34.24 fg	34.80 fg
$I_1 \times N_2$	403	410	324	334	5.59 de	5.73 e	36.44 ef	37.00 ef
$I_1 \times N_3$	443	452	363	368	6.94 b	7.06 c	41.04 bcd	51.54 bcd
$I_1 \times N_4$	478	482	373	374	8.28 a	8.40 a	46.38 a	46.69 a
$I_1 \times N_5$	471	474	366	370	7.76 a	7.85 b	42.96 bc	43.28 ab
$I_2 \times N_1$	305	311	273	377	3.57 f	3.62 gh	32.46 gh	32.51 g
$I_2 \times N_2$	346	350	318	321	5.63 de	5.77 e	40.26 bcd	40.80 bcd
$I_2 \times N_3$	375	380	333	336	6.44 bc	6.61 cd	41.99 bc	42.87 abc
$I_2 \times N_4$	412	418	348	354	6.62 bc	6.76 cd	43.14 ab	41.58 bcd
$I_2 \times N_5$	405	411	338	351	6.28 c	6.42 d	38.49 de	37.32 def
$I_3 \times N_1$	296	298	245	248	3.42 f	3.44 h	30.51 h	27.72 h
$I_3 \times N_2$	308	311	304	310	5.11 e	5.12 f	40.76 bcd	38.71 cde
$I_3 \times N_3$	355	361	325	332	5.48 de	5.46 ef	42.83 bc	40.45 bcd
$I_3 \times N_4$	407	410	334	340	5.72 d	5.84 e	41.63 bcd	41.42 bcd
$I_3 \times N_5$	395	398	334	336	5.67 d	5.77 e	39.63 cde	38.21 def
Significance	NS	NS	NS	NS	**	**	*	*
LSD 5%	35	167	32	35	0.53	0.52	3.39	4.44
CV %	5.49	5.63	6.42	6.28	5.50	5.29	5.09	6.75

Means sharing different letters in a column vary significantly at $P \leq 0.05$.

LSD = least significant difference; *, ** = significant at 5% and 1%, respectively; CV = coefficient of variation; NS = nonsignificant; I_1 = 525 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, R1, and R3 stages); I_2 = 450 mm ha^{-1} (irrigation in the V6, V12, VT, R1, and R3 stages); I_3 = 375 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, and R3 stages); N_1 = 0 kg ha^{-1}; N_2 = 75 kg ha^{-1}; N_3 = 150 kg ha^{-1}; N_4 = 225 kg ha^{-1}; and N_5 = 300 kg ha^{-1}.

Table 4. Effect of irrigation and nitrogen treatments on water and nitrogen use efficiency.

Treatments	**Water use efficiency** (kg ha^{-1} mm^{-1})		**Nitrogen use efficiency** (kg grain kg^{-1} N)	
	2009	**2010**	**2009**	**2010**
I_1	14.50 a	14.71 a	15.44 a	15.35 a
I_2	12.26 b	13.24 ab	13.86 a	14.33 a
I_3	11.36 c	11.48 b	10.81 b	10.84 b
LSD 5%	0.65	1.98	2.51	3.33
Significance	**	**	*	*
N_1	11.30 c	8.43 d	--	--
N_2	11.69 c	12.43 c	24.53 a	24.79 a
N_3	12.90 b	14.26 b	17.89 b	18.00 b
N_4	14.01 a	15.65 a	14.53 c	14.78 c
N_5	13.65 a	14.94 ab	9.89 d	10.00 d
LSD 5%	0.52	0.91	2.18	2.08
Significance	*	**	**	**
Linear	**	**	**	**
Quadratic	*	**	**	**
Cubic	**	*	**	**
$I_1 \times N_1$	12.48 dc	9.06 f	--	--
$I_1 \times N_2$	12.93 cd	12.76 d	23.51 b	23.47 b
$I_1 \times N_3$	14.80 b	15.67 c	20.78 bc	20.64 bc
$I_1 \times N_4$	16.48 a	18.64 a	19.81 bc	19.72 c
$I_1 \times N_5$	15.80 a	17.41 b	13.10 d	12.93 de
$I_2 \times N_1$	10.93 g	8.24 f	--	--
$I_2 \times N_2$	11.14 fg	13.07 d	27.51 a	28.58 a
$I_2 \times N_3$	12.65 de	14.97 c	19.16 c	19.89 bc
$I_2 \times N_4$	13.66 c	15.33 c	13.57 d	13.94 d
$I_2 \times N_5$	12.92 cd	14.59 c	9.06 e	9.33 ef
$I_3 \times N_1$	10.47 g	7.98 f	--	--
$I_3 \times N_2$	11.00 fg	11.47 e	22.58 bc	22.31 bc
$I_3 \times N_3$	11.23 fg	12.14 de	13.73 d	13.47 d
$I_3 \times N_4$	11.87 ef	12.98 d	10.21 de	10.67 def
$I_3 \times N_5$	12.23 de	12.81 d	7.51 e	7.74 f
Significance	**	**	**	**
LSD 5%	0.89	1.18	3.78	3.60
CV %	4.58	5.32	16.78	15.82

Means sharing different letters in a column vary significantly at $P \leq 0.05$.
LSD = least significant difference; *, ** = significant at 5% and 1%, respectively; CV = coefficient of variation; NS = nonsignificant; I_1 = 525 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, R1, and R3 stages); I_2 = 450 mm ha^{-1} (irrigation in the V6, V12, VT, R1, and R3 stages); I_3 = 375 mm ha^{-1} (irrigation in the V4, V8, V14, V18, VT, and R3 stages); N_1 = 0 kg ha^{-1}; N_2 = 75 kg ha^{-1}; N_3 = 150 kg ha^{-1}; N_4 = 225 kg ha^{-1}; and N_5 = 300 kg ha^{-1}.

maximum grain yield (Gheysari et al. 2009; Hammad et al. 2011a) as it ultimately results in lower NUE. The use of N rates above 225 kg ha^{-1} resulted in lower NUE (Table 4). As observed by Paolo and Rinaldi (2008), NUE could be increased only at a specific rate of N in the presence of lower soil moisture content.

The fact that the highest WUE was achieved with the application of more water and N reveals that both water and N are yield-limiting factors in semiarid environments. The highest NUE in the experiment was recorded when N fertilizer was used in an intermediate combination of irrigation and N treatments (i.e. the interaction of $I_2 \times N_2$). This reflects that the interaction of $I_2 \times N_2$ can be considered to be the water and N BMP for growing maize under semiarid environmental conditions.

In semiarid Pakistan, increased applications of water and nitrogen beyond their optimal levels are not wise practices to achieve optimum maize yield. The best water and nitrogen management practices may comprise supplemental irrigation equivalent to a depth of 525 mm per 7 irrigations and a nitrogen application of 225 kg ha^{-1} per growing season to achieve optimum maize yield.

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