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Optimizing irrigation and nitrogen requirements for maize through empirical modeling in semi-arid environment

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Abstract

Uncertainty in future availability of irrigation water and regulation of nutrient amount, management strategies for irrigation and nitrogen (N) are essential to maximize the crop productivity. To study the response of irrigation and N on water productivity and economic return of maize (*Zea mays* L.) grain yield, an experiment was conducted at Water Management Research Center, University of Agriculture Faisalabad, Pakistan in 2015 and 2016. Treatments included of full and three reduced levels of irrigation, with four rates of N fertilization. An empirical model was developed using observed grain yield for irrigation and N levels. Results from model and economic analysis showed that the N rates of 235, 229, 233, and 210 kg ha^{-1} were the most economical optimum N rates to achieve the economic yield of 9321, 8937, 5748, and 3493 kg ha^{-1} at 100%, 80%, 60%, and 40% irrigation levels, respectively. Economic optimum N rates were further explored to find out the optimum level of irrigation as a function of the total water applied using a quadratic equation. The results showed that 520 mm is the optimum level of irrigation for the entire growing season in 2015 and 2016. Results also revealed that yield is not significantly affected by reducing the irrigation from full irrigation to 80% of full irrigation. It is concluded from the study that the relationship between irrigation and N can be used for efficient management of irrigation and N and to reduce the losses of N to avoid the economic loss and environmental hazards. The empirical equation can help farmers to optimize irrigation and N to obtain maximum economic return in semi-arid regions with sandy loam soils.

Keywords Water scarcity · Irrigation amount · N losses · Water productivity

Introduction

Water is a key component for sustaining quality of life and has a direct impact on all sectors such as agriculture, forestry, and fisheries. Water scarcity is a serious problem in arid and semi-arid regions of the world (Abu-allaban et al. 2015). Management of irrigation water to increase agricultural production is particularly important in these regions (Bizikova and Julie 2015). More than 80% of Pakistan has an arid and semi-arid climate, where irrigation management is becoming critical due to increased temperatures and decreased rainfall (Naheed and Mahmood 2006). Pakistan is one of the most water-stressed countries in the world due to high population growth. Water resources of Pakistan are rapidly declining and it is predicted that they will not be able to provide sustainable production in semi-arid agroecosystem in the near future (Bastida et al. 2017). The per capita availability of water has decreased from 5300 m^3 in 1950s to 1000 m^3 in 2011 and future scenarios project it to be 855 m^3 in 2020 and even lower at 769 m^3 by 2050 (Monheit 2011). This will result in severe water shortages for the next generation of farmers. Future water requirements and challenges impose a serious threat to Pakistan due to its agrarian economy where wheat, rice, and maize are primary food crops (Kokab and Nawaz 2013). In future scenarios, high volume of water for irrigation is not a viable option. Judicious use of water is needed for food security (Mancosu et al. 2015)

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Maize is one of the world's principal food crops, feeding both human and livestock (Tah et al. 2008). In Pakistan, the production area for maize is the third largest, after wheat and rice (Government of Pakistan 2017). Pakistani soil and climatic conditions are ideal for maize production; however, yields and profits are still low due to improper irrigation and fertilization practices (Sharar et al. 2003). Amiri et al. (2015) found a 30–40% reduction in maize yields when the crop was not irrigated at critical growth stages. An even higher reduction, by 66–96%, was observed when there was no irrigation at tasseling and ear formation. Water stress at the vegetative and tasseling stages reduces leaf size, water potential, and plant height, leading to 28–32% loss in final biomass (Çakir 2004). Previous studies have shown that water deficit at grain-filling stage decreases the yield by 33%, due to lower grain weight, harvest index, and water-use efficiency (Wight and Hanks 2003). Complete withdrawal of irrigation at the vegetative and flowering stages resulted in higher yield losses, while 25% water deficit at vegetative, flowering, and grain filling stages improved the yields (Kuşçu and Demir 2012). On the other hand, some water stress during the early and late stages of the maize crop enhanced water-use efficiency and did not show any significant reduction in yield (Meskelu et al. 2014). Adequate water at the vegetative and reproductive stages of the maize crop increases the metabolic activity in plant cells and mineral absorption by the crop (Hirel et al. 2011). Saeed et al. (2017) found that less water could be used at vegetative and reproductive stages without significantly reducing the grain yield in wheat under semi-arid conditions. Similar results were found by Irmak et al. (2016) for maize. Regulated deficit irrigation (RDI) can increase the yield by 10–20% in maize as compared to irrigation strategy where stress level remains constant throughout growth stages in semi-arid areas (Domínguez et al. 2012). Strategic change in irrigation management to minimize yield reduction per unit area can increase the water productivity and net income of farmers (Fereres and De Rabanales 2007). Reduced irrigation, i.e., regulated deficit irrigation (RDI) is key technology and effective strategy to improve the water-use efficiency, to cope with water scarcity and maximize water productivity of the crop (Majnooni-heris et al. 2014).

Productivity of maize also depends upon the availability of N and its relationship with irrigation water (Xiukang 2017). N is an essential element and its deficiency causes growth retardation and yield losses (El Zubair et al. 2015). N stress affects leaf expansion, rubisco activity, chlorophyll content, and radiation interception (Hassan et al. 2010). Both excess and deficiency of N can interrupt the partition of photoassimilates between vegetative and reproductive stages ultimately affecting yield in semi-arid conditions (Singh and Hadda 2016). It was found that biomass and yield is increased by N up to 200 kg ha^{-1}, but further addition of N did not increase the biomass and yield significantly (Biswas and Ma 2016). Thus, over fertilization may cause many environmental hazards, such as acidification of soil and water resources and eutrophication of aquatic and marine ecosystem, and can accelerate depletion of the ozone layer (Bashir et al. 2013).

An optimal combination of irrigation and N use can increase the crop growth and yield (Sajedi et al. 2009). The relationship between water and nitrogen is very a useful tool to maximize economic return from crop (Kibe et al. 2006). The availability of water and climatic factors both should be considered to manage nitrogen (Derby et al. 2005). Higher application of N and irrigation beyond the optimal level is not a good management strategy (Hammad et al. 2012). Both maximum yield and maximum economic profit were observed in maize by application of optimal rates of irrigation and N under semi-arid condition of Northeast China (Yin et al. 2014). Different optimum levels of irrigation and nitrogen are recommended in Pakistan in previous studies. Randhawa et al. (2012)) found 250 kg ha^{-1} N as optimum for six irrigations to get maximum yield of maize in semi-arid environment. Khaliq et al. (2009) found 300 kg ha^{-1} N as optimum for eight irrigations and Abbas et al. (2005) found 200 kg ha^{-1} N as optimum for eight irrigations in semi-arid environment. Hammad et al. (2011) found reduction in maize yield for skipping irrigations at different vegetative growth stages of maize for different nitrogen levels and reported reduction in yield when nitrogen was reduced or increased from 250 kg ha^{-1}.

We have different recommendations and rare use of analytical methods to optimize irrigation and nitrogen in semi-arid environment (Abbas et al. 2005; Khaliq et al. 2009; Randhawa et al. 2012).

The goal of this study is to determine the optimal amount of N and irrigation to maximize economic return using field experiments and analytical techniques. Specific objectives of the study are: (1) to estimate the response of different irrigation and N applications for maximum yield and (2) to develop an empirical model for semi-arid environment to optimize the amount of N and volume of irrigation for maize. The methodology and the model developed here could be applied to semi-arid regions with sandy loam soils.

Materials and methods

Field experiment

A field experiment to obtain a dataset for the study was conducted at the Water Management Research Center (WMRC), University of Agriculture, Faisalabad, Pakistan (31° 23′ N, 73° 00′ E) during the spring seasons in 2015 and 2016. Maize hybrid Pioneer-1543 was planted on 14 February in both years. The maize crop was sown on ridges with a dibbler. The seeding rate was 25 kg ha^{-1}, with a plant-to-plant distance of 20 cm and a row distance of 75 cm. The experiment was conducted in a randomized complete block design with a split plot arrangement. Four irrigation regimes were applied in the main plots and four N levels in the subplots. Each treatment was replicated three times. The size of each plot was 3.5 m × 6 m. All plots received the recommended amount of P in the form of ammonium phosphate and K in the form of sulfate of potash at 125 kg ha^{-1} (Khan et al. 2011). All other, agronomic practices such as tillage, weed, and pest control, were kept uniform for all the treatments.

Soil and weather data

Physical, hydraulic, and chemical analyses of the soil were conducted prior to planting (Table 1). Ten representative samples were obtained from 0 to 15 and 15 to 30 cm depths using soil auger. These samples were mixed separately to make a composite sample and were analyzed. Percentage of silt and clay were determined by Bouyoucos Hydrometer method using 1% sodium hexametaphosphate as a dispersing agent. The texture class of soil was determined using the international texture triangle (Moodie and Smith 1959). Available phosphorus was measured by a spectrometer using the Olson method (Homer and Pratt 1961). Potassium was determined by a flame photometer (Mehlich 1953). Total N was measured by using the Kjeldahl method (Bremne 1960). Electrical conductivity of soil was determined by Field Scout EC 110 Meter following the protocol by Mehlich (1953). Saturation percentage was determined from a paste, which was brought to saturation by adding water while stirring (Johnson 1962). Field capacity of the soil was determined by following the protocol described by Karkanis (1983). Daily weather data for the two growing seasons were obtained from an observatory at WMRC.

Figure 1 shows the daily weather data during the growing seasons of 2015 and 2016. The 2016 was slightly warmer than 2015, with 25 mm less rainfall and higher maximum and minimum temperatures by about 1.74 °C and 0.52 °C, respectively. However, the mean sunshine hours during the two growing seasons were similar. Interannual variability in amount and distribution of rainfall was also observed. The total rainfall of 117.1 and 91.8 mm was recorded in 2015 and 2016 respectively (Fig. 1).

Water application using a cutthroat flume

The amount of water applied for full irrigation was measured by a cutthroat flume. The recommended water depth for maize irrigation is 75 mm (Hammad et al. 2012). The moisture content was determined only before the first irrigation using time-domain reflectometer which was 13% on volumetric basis. The 96 × 36 in. cutthroat flume was selected and installed in the center of watercourse. Soil was placed around the flume, to force the flow of water completely through the flume. Readings were measured from the stilling wells at the inlet and outlet sections of the flume. The discharge of water was calculated from the free-flow calibration table. The time of full irrigation was calculated from the following formula (Skogerboe et al. 1967).

$$t = \frac{(A \times d)}{Q} \quad (1)$$

where "t" is time of irrigation for a given area in second, "A" is area to be irrigated in m^2, and "d" is the depth of water applied in mm. "Q" is discharge from the flume in $m^3 s^{-1}$. The time of full irrigation was calculated, and irrigation was applied using flood irrigation method through ditches. The time of irrigation

Table 1 Physical, chemical, and hydraulic properties of soil at the experimental site

a) Soil physical properties				
Depth	Sand (%)	Silt (%)	Clay (%)	
0–15 cm	63.3	21.0	17.7	
15–30 cm	62.6	21.4	17.9	
b) Chemical properties				
Year	2015		2016	
Depth	0–15	15–30	0–15	15–30
N %	0.036	0.035	0.035	0.036
Available phosphorus (ppm)	7.10	7.15	6.80	7.05
Available potassium (ppm)	60.5	62.01	65.2	66.6
EC (dS m^{-1})	1.75	1.77	1.79	1.78
Soil pH	8.15	8.12	8.16	8.11
Organic matter (%)	0.49	0.48	0.47	0.48
c) Hydraulic properties				
Saturation (%)	35.5	37.5	36.01	37.2
Field capacity (%)	23	23.2	22.1	22.3

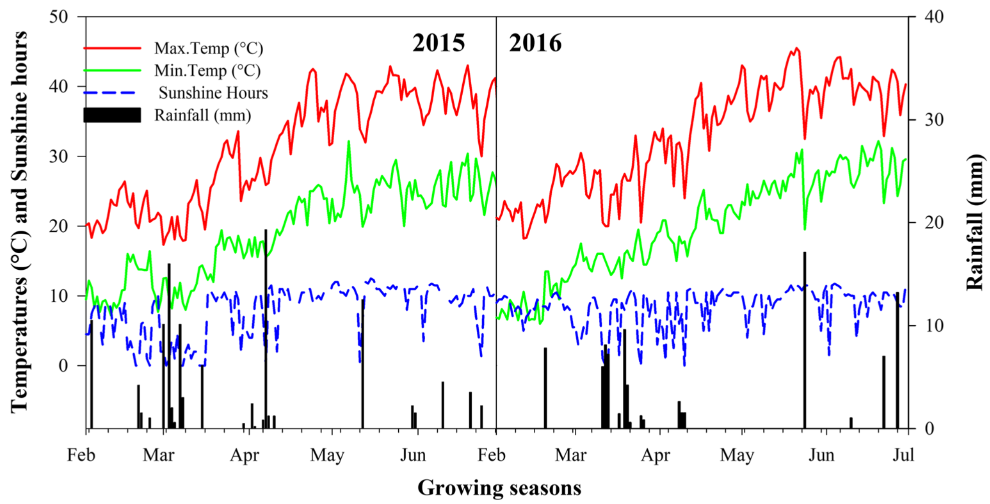

Fig. 1 Daily weather data at the experimental site during the growing seasons in 2015 and 2016

water for 80%, 60%, and 40% was calculated from the time of full irrigation water and reduced accordingly.

Table 2 provides details of the four irrigations and four N treatments conducted at various growth stages. Table 3 shows the number and amount of irrigation at critical growth stages of maize during each irrigation treatment.

Data collection

Vegetation samples were obtained every 2 weeks to estimate the leaf area index (LAI) and total dry matter (TDM). Three plants were harvested from each subplot; fresh weights of leaves and stems were measured. A subsample (10 g) of leaves was used to measure leaf area using Laser Area Meter (model CI-203). To obtain TDM, leaf and stem tassel and cob (when tassel and cob developed) were oven dried at 70 °C for 48 h. LAI was determined as a ratio of leaf area to ground area (Watson 1947). At maturity, half of the subplot of each treatment was harvested and a subsample of 10 plants was used to determine the number of grains per cob and 1000-grain weight.

Statistical analysis

Combined year analyses were done with all data from both growing seasons; the significance of different levels of irrigation and N on recorded data was analyzed using Fisher's analysis of variance technique (ANOVA). The differences among treatment means of each observed variable were compared using the honest significant difference (HSD) test at 0.05 probability. PROC GLM under SAS V9.4 software was used to perform statistical analysis (SAS Institute 2013). Regression analysis was conducted to study the response of grain yield to various levels of irrigation and N.

Calculation of optimum N

The optimum level of N was calculated for each level of irrigation by fitting a quadratic equation, with a, b, and c as its coefficients.

$$Y = aN^2 + bN + c \quad (2)$$

Table 2 Irrigation and N treatments at various stages in the experiment

	Growth stages
Factor A: irrigation	
Full irrigation (100%)	V4, V8, V12, V16 (leaf stages), tasseling, blister, milking, and dough
80%	
60%	
40%	
Factor B: N	
160 kg ha^{-1}	40% at sowing, 20% at V4, 20% at V12, and 20% at initiation of tasseling
200 kg ha^{-1}	
240 kg ha^{-1}	
280 kg ha^{-1}	

Table 3 Amount of the irrigation water applied at critical growth stages of maize hybrid in single event in 2015 and 2016

Growth stages	Water applied in 2015				Water applied in 2016			
	$I_1 = 100\%$	$I_2 = 80\%$	$I_3 = 60\%$	$I_4 = 40\%$	$I_1 = 100\%$	$I_2 = 80\%$	$I_3 = 60\%$	$I_4 = 40\%$
V4	77	61	46	31	76	61	46	30
V8	75	60	45	30	75	60	45	30
V12	73	58	44	29	74	59	44	30
V16	74	59	44	30	75	60	45	30
Tasseling	72	58	43	29	75	60	45	30
Blister	75	60	45	30	75	60	45	30
Milking	74	59	44	30	76	61	46	30
Dough	75	60	45	30	74	59	44	30
Total water (mm)	595	475	356	239	600	480	360	240
Total water input (irrigation plus rainfall)	712	592	473	356	691	571	451	331

The optimal amount of N (N_optimum) for maximum grain yield (Y) of maize was calculated for each irrigation regime using Eq. 3. This approach has previously been used for wheat crop under semi-arid conditions of Pakistan (Saeed et al. 2017). A similar technique was also used by Pandey et al. (2000) for maize under a semi-arid Sahelian environment in Niamey, Niger.

$$N_{optimum} = \frac{-b}{2a} \tag{3}$$

For each irrigation treatment, Eq. 4 was used to predict grain yield for 1–280 kg ha^{-1} of N. The benefit-cost ratio (BCR) defined as the ratio of income from grain yield to the total input cost was estimated for simulated yield to determine the economically optimum level of N that would result in the maximum BCR for each irrigation treatment (Saeed et al. 2017). In this analysis, all input costs remained the same across all treatments, except the cost of four irrigations and 1–280 kg ha^{-1} of N. The N cost was US \$0.76/kg, irrigation cost was US \$23.4/irrigation for 1 ha, and the maize grain price was US \$0.24/kg (Agriculture management system punjab 2016).

Excess N (N) % was calculated as

$$\text{Excess N\%} = \frac{\text{Applied N}\left(\text{kg ha}^{-1}\right) - \text{Economically Optimum N}\left(\text{kg ha}^{-1}\right)}{\text{Optimum N}\left(\text{kg ha}^{-1}\right)} \times 100 \tag{4}$$

For each of the four irrigation levels, quadratic relationships were developed between the mean water applied in the two growing seasons and the economically optimal N for that irrigation levels. Economically optimal water input was calculated using an equation similar to Eq. 1. The amount of water applied in both years and economically optimum N were used in Eq. 1 to calculate the optimum water. Water productivity (kg·mm ha^{-1}) was calculated as a ratio of the grain yield and water applied, a similar formula was used by Cook et al. (2006) for the calculation of water productivity.

Results

Effect of different levels of irrigation and N on maize growth

Plant height was significantly affected by various levels of irrigation and N. The interaction effect of irrigation and N on plant height was highly significant and the year effect was also found significant for both year 2015 and 2016, as shown in Table 4. Higher plant height of 221 cm was observed in 2015, while a lower plant height of 214 cm was observed in 2016. Table 5 shows a that maximum plant height of 252.24 cm was attained at full or 100% irrigation with 280 kg ha^{-1} N and it was statistically similar to the height at 80% irrigation level with 200 and 240 kg ha^{-1} N. Lowest plant height of 169.4 cm was observed at the 40% irrigation level with 240 kg ha^{-1} N. It was also similar to 40% irrigation treatment with 280 kg ha^{-1} N. Thus, an increase in N application for full and 80% irrigation did not show any significant difference, but a further increase in N for 60 and 40% irrigation levels decreased the plant height.

The effect of irrigation and N on LAI was highly significant ($P < 0.001$) (Fig. 2). Low moisture affects the availability of N, thus increasing N under dry conditions did not affect the LAI. A maximum LAI of 5.97 was observed for full irrigation with 280 kg ha^{-1} N and it was statistically similar to full and 80% irrigation with 240 kg ha^{-1} N. A minimum LAI of 2.44 was observed at the 40% irrigation level with 160 kg ha^{-1} N, as shown in Table 5. The LAI increased slowly during vegetative stages, but the rate was higher during tasseling and ear formation. The crop attained the maximum LAI at 60–70 days

Table 4 Analysis of variance table for various levels of irrigation and N on yield attributes for maize during years 2015–2016

Source of variance	Plant height (cm)	Plant population (m^{-2})	Grains per cob (#)	Leaf area index max.	1000-Grain weight (g)	Grain yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)	WP (kg ha^{-1} mm^{-1})
Year (Y)	0.022	0.410	0.010	0.396	0.327	0.271	0.238	0.002	0.001
Block (year)	0.89	0.104	0.140	0.001	0.004	0.008	0.068	0.276	0.004
Irrigation (A)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.0001	0.001
YA	0.962	0.851	0.6505	0.614	0.830	0.977	0.628	0.596	0.385
Main error	0.28	0.028	0.139	0.438	0.410	0.025	0.016	0.439	0.025
Nitrogen (B)	0.001	0.001	0.001	0.001	0.001	0.001	0.0001	0.001	0.0001
AB	0.001	0.0007	0.951	0.01	0.008	0.001	0.001	0.193	0.001
YB	0.94	0.886	0.668	0.514	0.992	0.979	0.882	0.625	0.877
YAB	0.99	0.991	0.995	0.972	0.999	1.000	0.999	0.994	0.999
CV	5.01	10.11	5.84	6.74	5.85	8.32	8.79	5.22	7.91
R^2	0.93	0.90	0.84	0.97	0.92	0.97	8.79	0.878	0.90
RMSE	4.68	0.62	20.53	0.28	21.80	506.74	1439.71	1.92	1.15

Note: * and ** are significant at 0.05 and 0.01 probability level, respectively; # number, *WP* water productivity

after sowing and thereafter showed a declining trend in both years, as shown in Fig. 2a, b.

Effect of different levels of irrigation and N on maize yield

Plant population was also highly affected ($P < 0.007$) by irrigation and N, as shown in Table 4. A maximum plant population of 8 plants m^{-2} was observed at full irrigation with 280 kg ha^{-1} N which was statistically similar with full and 80% irrigation with 240 kg ha^{-1} N. A minimum plant population of 4.16 plants m^{-2} was recorded in the 40% irrigation level with 280 kg ha^{-1} N, as shown in Table 5. When there is an increase in N amount from 160 to 200 kg ha^{-1} in full irrigation and 80% irrigation, there is a significant increase in plant population, but

Table 5 Interactive effect of irrigation and N regimes on growth and yield component of maize hybrid during the years 2015–2016

Irrigation	Nitrogen (kg ha^{-1})	Leaf area index max.	Plant height (cm)	Plant population (m^{-2})	1000-Grain weight (g)	Grain yield (kg ha^{-1})	Biological yield (kg ha^{-1})	WP (kg ha^{-1} mm^{-1})
$I_1 = 100\%$	$N1 = 160$	3.913 def	234.17 abc	6.00 cde	379.0 bcd	5956.3 b	15,012.0 d	10.0 h
	$N2 = 200$	5.21 bc	244.14 a	7.50 ab	443.6 a	8604.4 a	20,770.4 bc	14.4 def
	$N3 = 240$	5.78 ab	250.09 a	7.83 a	430.3 a	9187.4 a	23,659.7 ab	15.4 cd
	$N4 = 280$	5.97 a	252.24 a	8.00 a	411.4 abc	8800.9 a	25,059.6 a	14.7 de
$I_2 = 80\%$	$N1 = 160$	3.72 def	220.2 bcd	5.60 def	378.1 dc	5768.5 b	14,497.4 d	12.1 fgh
	$N2 = 200$	5.06 c	237.27 ab	7.16 abc	436.2 a	8333.9 a	20,349.0 c	17.5 abc
	$N3 = 240$	5.57 abc	247.99 a	7.66 a	423.8 ab	8861.7 a	23,075.1 abc	18.6 a
	$N4 = 280$	5.74 ab	247.61 a	7.50 ab	410.9 abc	8504.4 a	24,623.7 a	17.8 ab
$I_3 = 60\%$	$N1 = 160$	2.70 h	196.64 ef	4.83 efg	340.4 def	4002.5 c	10,978.8 ef	11.2 gh
	$N2 = 200$	3.62 ef	197.27 ef	5.66 def	377.8 dc	5349.6 b	13,803.5 de	14.9 de
	$N3 = 240$	4.19 de	214.75 cde	6.16 dc	371.8 dc	5703.4 b	14,962.4 d	15.9 bcd
	$N4 = 280$	4.28 d	220.12 bcd	6.33 bcd	347.7 de	5546.0 b	15,271.4 d	15.5 bcd
$I_4 = 40\%$	$N1 = 160$	2.44 h	189.02 gf	4.50 gf	312.3 efg	2888.5 d	8949.3 f	12.1 fgh
	$N2 = 200$	2.92 gh	199.12 def	5.16 defg	324.1 ef	3653.3 dc	11,176.5 ef	15.3 cd
	$N3 = 240$	2.97 gh	169.4 g	4.5 gf	297.8 gf	3237.7 dc	9721.0 f	13.5 def
	$N4 = 280$	3.35 gf	184.58 gf	4.16 g	274.8 g	3006.6 dc	9888.0 f	12.6 efg

Values with the same lowercase letters are statistically similar while different letters show the difference among treatment means

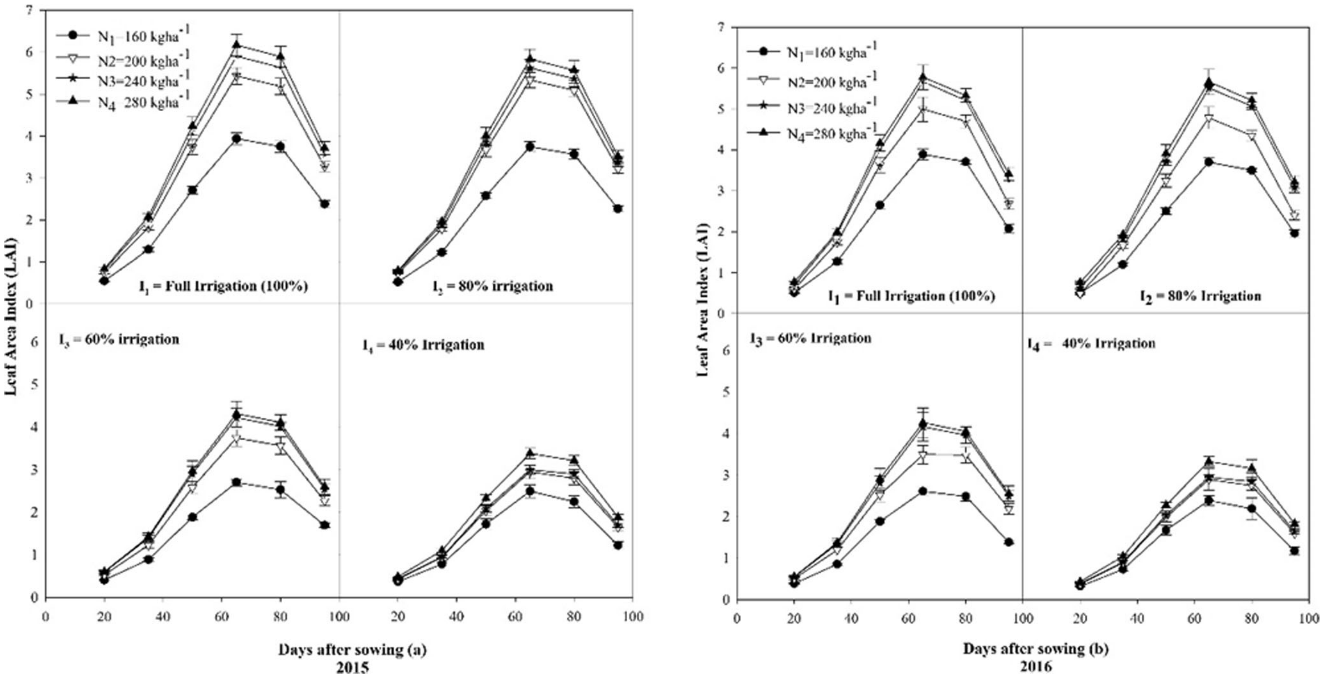

Fig. 2 Time series leaf area index of maize at various level of irrigation and N for the years 2015–2016

further increase in N from 240 to 280 kg ha^{-1} N did not show any significant difference.

The number of grains per cob were significantly ($P <$ 0.0001) affected by irrigation and N, as shown in Table 4. Season affected the grains per cob, in which a higher number of grains per cob of 364.47 was recorded in 2015, while fewer of grains per cob of 338.85 were observed in year 2016, as shown in Table 6. The number of grains per cob was reduced significantly ($P < 0.001$) for the treatment at which 40% irrigation was applied. Increasing the N from 160 to 200 kg ha^{-1} increased the grains per cob but a further increase in N from 240 to 280 kg ha^{-1} did not show any significant differences. A maximum number of grains per cob of 376.61 was recorded at full irrigation which was statistically similar to the 80% irrigation level, while a minimum no. of grains per cob of 315.08 was observed at the 40% irrigation level, as shown in Table 6. In the case of N, the maximum number of grains per cob of 364.84 was recorded at 280 kg ha^{-1} N which was statistically similar to 240 kg ha^{-1} N. While a minimum number of grains per cob of 327.2 was observed at 160 kg ha^{-1} N.

Irrigation and N significantly ($P < 0.008$) affected the weight of 1000 grains. There was significant increase in the 1000-grain weight with increasing N from 160 to 200 kg ha^{-1} in the four irrigation levels, but an increase in N from 240 to 280 kg ha^{-1} N did not show any significant difference. A maximum 1000-grain weight of 443.6 g was observed when full irrigation with 200 kg ha^{-1} N was applied. It was statistically similar to treatments of full irrigation with 240 and 280 kg ha^{-1} N, 80% irrigation with 200, 240, and 280 kg ha^{-1} N. While minimum 1000-grain weight of 274.8 was observed where 40% irrigation level with 280 kg ha^{-1} N was applied, as shown in Table 7.

Grain yield was significantly ($P < 0.001$) affected by different levels of irrigation and N, as shown in Table 4, but season did not have any effect on grain yield. The highest grain yield of 9187.4 kg ha^{-1} was recorded in full irrigation with 240 kg ha^{-1} N, which was statistically at par with full irrigation treatment with 200 and 280 kg ha^{-1} N and the 80% irrigation treatment with 200, 240, and 280 kg ha^{-1} N. The lowest grain yield of 2888.5 kg ha^{-1} was observed in the 40% irrigation level with 160 kg ha^{-1} N, which was statistically similar to the other three levels 200, 240, and 280 kg ha^{-1} of N. The response of irrigation

Table 6 Effect of irrigation and N on yield attributes of maize during the years 2015 and 2016

Treatments		No. of grain per cob	Harvest index%
Year	2015	364.47 a	38.33 a
	2016	338.85 b	35.31 b
Irrigation	$I_1 = 100\%$	376.61 a	39.02 a
	$I_2 = 80\%$	371.57 a	38.67 a
	$I_3 = 60\%$	343.44 b	37.37 a
	$I_4 = 40\%$	315.08 c	32.21 b
Nitrogen kg ha^{-1}	$N_1 = 160$	327.2 c	37.09 a
	$N_2 = 200$	350.5 b	38.56 a
	$N_3 = 240$	361.02 ab	37.23 a
	$N_4 = 280$	364.84 a	34.39 b

Values with the same lowercase letters are statistically similar while different letters show the difference among treatment means

Table 7 Quadratic equation for maize grain yield response to different levels of N (x, kg ha^{-1})

Irrigation regimes	Equation	R^2
$I_1 = 100\%$	$y = -0.4742x^2 + 231.42x - 18878$	0.99
$I_2 = 80\%$	$y = -0.4567x^2 + 222.7x - 18127$	0.98
$I_3 = 60\%$	$y = -0.2351x^2 + 115.9x - 8498$	0.99
$I_4 = 40\%$	$y = -0.1556x^2 + 68.31x - 3990$	0.72

and N showed that greater application of N with low moisture availability decreased grain yield. With full irrigation, grain yield improved by 6.3% with 240 kg ha^{-1} N when compared to 200 kg ha^{-1} N. Grain yield also improved by 5.9% with 80% irrigation at 240 kg ha^{-1} N compared to 200 kg ha^{-1}. The response to N was different in the 40% irrigation treatment. The yield increased by 20.9% with 40% irrigation at 200 kg ha^{-1} N compared to 160 kg ha^{-1} N, but a further increase in N from 200 to 240 kg ha^{-1} decreased yield by 12%, as shown in Table 5.

Combined irrigation and N affected the biological yield significantly ($P < 0.001$). Maximum biological yield (25,059 kg ha^{-1}) was observed with full irrigation at 280 kg ha^{-1} N, which was statistically similar to treatments of full and 80% irrigation with 240 kg ha^{-1} N (Table 5). Lowest biological yield of 8949 kg ha^{-1} was recorded with 40% irrigation at 160 kg ha^{-1} N, which was statistically similar to 200, 240, and 280 kg ha^{-1} N. Biological yield was decreased by increasing the N rate under low moisture content. Biological yield increased by 13% in full and 80% irrigation levels with a N level of 240 kg ha^{-1} N as compared with 200 kg ha^{-1}, but under low moisture content as in 40% irrigation, there was a 13% reduction in yield at 240 kg ha^{-1} N compared with 200 kg ha^{-1} N.

Harvest index was significantly ($P < 0.002$) affected by season, irrigation ($P < 0.001$), and N ($P < 0.001$), as shown in Table 5. A higher harvest index of 38% was recorded in 2015 as compared to 35.31% in 2016. There was no significant difference in 1000-grain weight when irrigation volume was decreased from 100 to 60%. The minimum 1000-grain weight was recorded in 40% irrigation level. Within N levels, the highest harvest index of 38.56% was recorded at 200 kg ha^{-1} N, and it was statistically similar to 240 kg ha^{-1} N. The lowest harvest index of 34.39% was recorded with 280 kg ha^{-1} N. Thus, an increase in N rates at 280 kg ha^{-1} N caused the reduction in harvest index.

Effect of different levels of irrigation and N on water productivity (WP)

N and irrigation affected the water productivity (WP) significantly ($P < 0.001$), as shown in Table 4. Maximum WP of 18 kg ha^{-1} mm^{-1} was recorded in the 80% irrigation treatment with 240 kg ha^{-1} N. It was statistically at par with the treatments of 80% with 200 and 280 kg ha^{-1} N. Minimum WP of 10.10 kg ha^{-1} mm^{-1} was recorded where full irrigation with 160 kg ha^{-1} N was applied. Reducing the irrigation volume from 100 to 80% achieved maximum water productivity and grain yield. There was no increase in water productivity when N increased from 240 to 280 kg ha^{-1}, which could be due to an increase in biological yield as observed in 280 kg ha^{-1} (Table 5).

Optimum N rates and irrigation amount

Regression analysis showed a strong relationship with maize grain yield to N at various levels of irrigation. The R^2 values of these equations were relatively high, as shown in Table 7. From Table 8, the increase in N from 244 to 246 at 100 and 60% irrigation levels might increase the maize grain yield, but may not be economically beneficial for farmers. For this purpose, economically optimum N was calculated using the maximum value of BCR. Based on Table 8, economically optimum N levels were 3.6, 6.1, 5.4, and 4.3% less than the agronomic optimum N levels at full irrigation, 80%, 60%, and 40% irrigation regimes. Based on economically optimum N, the economical grain yields of 9321, 8937, 5748, and 3493 kg ha^{-1} were calculated at full, 80%, 60%, and 40% irrigation levels. Excess N was calculated from the difference between economically optimum N at N_{240} and N_{280} kg ha^{-1}. Results showed that excess N which was uneconomical and ranged from 2 to 13.7% for N_{240} kg ha^{-1} and 18.4 to 31.9% for N_{280} kg ha^{-1} at

Table 8 Optimum N rates from quadratic equation for maximum and economic yield, excessive N of maize at different levels of irrigation and N

Irrigation levels	Agronomic optimum N (kg ha^{-1})	Maximum yield (kg ha^{-1})	Economically optimum N	Economic yield (kg ha^{-1})	Excessive N% at N_{240} kg ha^{-1}	Excessive N% at N_{280} kg ha^{-1}
$I_1 = 100\%$	244	9359	235	9321	2.0	18.4
$I_2 = 80\%$	243	9038	229	8937	4.5	20.9
$I_3 = 60\%$	246	5791	233	5748	2.8	19.1
$I_4 = 40\%$	219	3507	210	3493	13.7	31.9
Mean	238	6923.7	226.75	6874.7	5.8	22.6

various irrigation regimes. It was interesting that under less irrigation (40% of full irrigation), less amount of N is required to achieve maximum economic yield. Economical optimum N rates were used to calculate the optimum level of irrigation for the growing season of maize. Results from quadratic equation ($\text{Irrigation}_{\text{optimum}} = -0.0003\ W^2 + 0.3123\ W + 155.15$) showed that the optimum amount of water for maize was 520 mm for the two growing seasons.

Discussion

Optimum levels of irrigation and nitrogen are very important to get good economic return and yield from maize crop. The use of both resources are also linked with climate and soil. In this study, a 2-year field trial was conducted to optimize both resources. There was no significant difference between plant height of maize when irrigated with full irrigation and 80% of full irrigation. Increasing N for 60 and 40% irrigation levels decreased plant height (Table 5). This could be due to unavailability of N at low moisture regimes. Harder et al. (2002) found that under drier conditions, N uptake was affected and it decreased the internodal length which resulted in reduced plant height. Kaplan et al. (2016) found that availability of N increased the rate of growth and development in meristem cells at adequate moisture supply which might increase plant height. Our results showed that irrigation and N significantly affected the LAI and peak LAI was recorded at 60–70 days after planting, as shown in Fig. 2. Maximum LAI with high rates of N was due to leaf expansion, which is due to more cell division and cell enlargement (Kar et al. 2014).

Moisture and N stress reduced the gain per cob (Table 5). Crop attained more number of grains per cob in 2015 as compared to 2016. In 2016, the average maximum temperature was 1.74 °C higher than 2015 and there was 26 mm less rainfall in 2016 than 2015. Under limited water conditions, the uptake of N decreases, affecting the quantity and activity of pollen before anthesis, and reducing the number of grains per cob and grain weight (Nguyen and Sutton 2009). Reducing the amount of irrigation to a certain limit (full irrigation to 80% of full irrigation) did not cause significant reduction in number of grains per cob. Reducing the number of irrigation from six to five did not show any significant effect on number of grains per cob but further reduction to four irrigation at different growth stages caused significant reduction in number of grains per cob (Ashraf et al. 2016) and we have same results.

Our results showed that increased maize yield could be obtained by optimizing both irrigation and N. In addition, reducing the volume of water from 100 to 80% did not show significant effect on grain yield which helped save water, as grain yield at 80% of full irrigation was at par with treatment where full irrigation was applied at all growth stages. This could be due to application of water at all critical growth stages of the crop. Previous studies have reported that water stress at any reproductive growth stages reduced the transpiration rate and photosynthetic activity, limited the tissue size of source and sink, and impaired the phloem loading, assimilate translocation, and dry matter production leading to reduction in grain yield (Farooq et al. 2009). Hammad et al. (2011) skipped irrigations at different growth stages of maize and found significant reduction in grain yield compared to the treatment where full irrigation was applied at all critical growth stages. The results revealed that applying reduced amount of water to a certain limit is a better management strategy as compared skipping irrigation at any growth stage of maize. In a 4-year study conducted by Irmak et al. (2016), similar results are reported where maize crop attained same yield when irrigated with full irrigation and 75% of full irrigation. Reduction in irrigation from 80% of full irrigation significantly reduced grain yield. This could be due to moisture stress and unavailability of N at low soil-moisture content. Ding et al. (2005) reported same results and found that under dry conditions, the availability of N to crop plant is reduced, causing deficiency of N that inhibits the photosynthetic activity by reducing the stromal and thylakoid protein in Calvin cycle that leads to decrease the grain yield. Water stress reduced the efficiency of N utilization and remobilization of assimilates from vegetative part to grains (Gonzalez-Dugo et al. 2010) which causes the reduction in grain yield. More biomass was observed with full irrigation and 280 kg ha^{-1} N as compared moisture-stressed treatments with the same amount of nitrogen. The reason for more biomass and less grain yield could be more vegetative growth due to excessive application of nitrogen which increases the crop water use and reduces the grain yield (Bennett et al. 1989).

The present study showed that water productivity increased by reducing the irrigation volume from 100 to 80%. Similar results were found by Geerts and Raes (2009) that application of reduced volume of irrigation water at vegetative and reproductive stages maximizes the water productivity.

Our study showed that the response of grain yield to N significantly followed a quadratic trend at various irrigation levels. Relationship of grain yield to N at 40% irrigation level was positive with $R^2 = 0.72$, but not as strong as other irrigation and N levels, as shown in Table 5. Pandey et al. (2000) reported the positive quadratic relationship between maize grain yield to N under deficit and full irrigation with R^2 ranging from 0.80 to 0.99 in clay loam soil.

The results showed that the economical N rates were 3.6 to 9.1% less than the agronomic optimum N, as shown in Table 8. Wang et al. (2014) found similar response that profitable N rates were 8 to 15% less than the agronomic optimum N rates. The variation in result might be due to cultivar, soil, and weather condition. Our study showed that optimum irrigation amount was 520 mm during the whole growing season of maize. These results are similar to Hammad et al. (2012) who reported 525 mm as optimum irrigation amount when applied at all critical stages in semi-arid condition.

This information is very useful for farmers in other semi-arid regions in Pakistan, provided that the soil condition is the same as in our study area. Farmers and stakeholders can use these equations to calculate the optimum levels of irrigation and N, because the lack of N can reduce yield, while an excess N can cause environmental hazards. In our study, reduced volume of water up to a certain limit can decrease the yield, but not significantly. Considering the judicious use of water, applying the measured volume of water by reducing at certain level has a potential to cope with the water shortage problem. In addition, the use of economically optimum N, according to availability of irrigation water, helps to increase the water productivity. Deficiency and excess use of N can cause the reduction in grain yield and environmental hazards.

Conclusion

The results showed that water could be saved, and water productivity could be increased, by applying the measured volume of irrigation at critical growth stages. Reducing the irrigation water from full irrigation of 100 to 80%, did not show any significant reduction in grain yield. Maximum water productivity was observed at 80% irrigation level. Results also revealed that crop N varies according to availability of water. The strong relationship between irrigation and N showed that N availability to crop plant depends upon the water availability.

Economical optimal N required by crop was found to be 210 kg ha^{-1} at 40% irrigation. Higher level of N 240 and 280 kg ha^{-1} caused the excess N, ranged from 2 to 31.9% at various levels of irrigation. Optimum use of N with respect to availability of irrigation water can help to increase the economic return of maize grain yield and may reduce the N loss due to excess use of N. The empirical equations from this study could be used to find out the optimum volume of irrigation and economical optimum rates of N in semi-arid environment of sandy loam soil.

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