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Maize response to different water, salinity and nitrogen levels: agronomic behavior

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Abstract

Soil water, salinity and nitrogen content are three major factors affecting crop production in arid and semi-arid areas. This study was performed in two years of 2009 and 2010 in a semi-arid area in order to investigate the effects of irrigation water quantity (as main plot), quality (saline water, as sub-plot), nitrogen fertilizer (as sub-sub plot) and their interactions on growth and yield of maize hybrid SC-704. The experimental design was split plot with three replications. Irrigation treatments consisted of I_1 (1.0 crop evapotranspiration (ET_c) + 0.25ET_c as leaching), I_2 (0.75I_1) and I_3 (0.5I_1) applied at 7-day intervals. The salinity treatments were 0.6 (fresh water), 2.0 and 4.0 dS m^{-1}. There were also three nitrogen (N) treatments including 0, 150 and 300 kg N ha^{-1}. The results showed that maize under water and salinity stress had longer vegetative stage period by 11 and 16% compared to the control, respectively. The most sensitive trait under water, salinity and nitrogen stress was grain yield (GY) which reduced by 52.3, 25.2 and 28.0%, for treatments of 0.5I_1, 4.0 dS m^{-1} and 0 kg N ha^{-1}, respectively. Based on water productivity (WP), applied water is more efficient for GY production under lower irrigation and N fertilizer usage. Grain yield surface function approached a maximum under I_2 and I_1 treatments in response to increasing water and N levels. The contour plots of GY were developed at each salinity level and showed that it could be a useful management device of irrigation and N for maize GY. Based on nitrogen use efficiency (NUE) and nitrogen recovery (NR), the N application rate of 150 kg ha^{-1} was the optimum rate for the study region especially under saline water conditions. Further, interaction result of the experimental factors showed that with adequate or limited fresh water supply, application of higher N rate (300 kg ha^{-1}) yielded higher GY. While under saline water application, lower N rates (150 kg ha^{-1}) was appropriate management for optimum maize GY with sufficient/non-sufficient irrigation. Furthermore, the threshold values of soil saturation extract, 50% GY reduction, and yield reduction coefficient of maize showed that in general maize did not tolerate salinity better under higher N application rate (300 kg ha^{-1}), although in some cases its sensitivity to salinity decreased by increasing N application rate.

Keywords: Agronomic response; Maize; Nitrogen; Saline water; Salinity indices.

Introduction

Maize (*Zea mays* L.) is one of the most important cereals for human consumption and animal feed and is grown for grain and forage. Water and nitrogen (N) are two important resources for crop production. Maize yield responds positively to an increase in the amount of water and N applied until their optimum level corresponding to maximum yield (Liu and Zhang, 2007; Zand-Parsa and Sepaskhah, 2001). However, there are concerns regarding the availability of resources, including water quantity and quality, as well as nitrate leaching due to excessive application of N.

Water and N shortage decrease crop yield. Drought stress reduces plant height (Soler et al., 2007), leaf area (Pandey et al., 2000), leaf photosynthesis (Shangguan et al., 2000), shoot growth and grain yield (Zand-Parsa et al., 2006; Payero et al., 2006). In addition, the amount of N supply affects leaf area index (LAI) and chlorophyll content (Majnooni-Heris et al., 2011; Ding et al., 2005). It has been reported that grain yield of maize (Tafteh and Sepaskhah, 2012) and wheat (Sepaskhah and Hosseini, 2008) increased by N application. Furthermore, an interaction between N and water supply has been demonstrated (Zand-Parsa et al., 2006). In other words, N uptake from soil is positively influenced by higher water supply (Ercoli et al., 2008). Excess application of water and N resulted in N leaching from the field (Sepaskhah and Tafteh, 2012). Crop N demand and N uptake are a function of both root and shoot growth (Grindlay, 1997). Therefore, an optimum amount of N based on the available amount of water is needed to improve crop yield. In fact, fertilizer N will not increase yield without sufficient water being available to plant, and increasing soil-water availability will not increase production without adequate N supply (Hu and Schmidhalter, 2005).

Increasing demand for water in the world, especially in the arid and semi-arid regions, has forced farmers to use poor quality water for irrigation, such as agricultural drainage water (saline water). Salinity is one of the serious environmental problems that causes osmotic stress and reduction in plant growth and crop productivity in irrigated areas. Suitable plant species and soil amendments are needed in salt affected agricultural areas for crop production. Salinity adversely affects yield, evapotranspiration, pre-dawn leaf water potential, stomatal conductance and leaf area of plants (Katerji et al., 2003). Yield reduction by salinity could also be attributed to the reduction of number and weight of grains, tubers and fruits (Asgari et al., 2012; Katerji et al., 2003).

Most salinity and N interaction studies in the field were conducted on N-deficient soils (Grattan and Grieve, 1999). Therefore, additions of N improved growth and/or yield (Khalil et al., 1967; Ravikovitch, 1973) when the degree of salinity was not severe. Grattan and Grieve (1999) stated that N-fertilisation did not increase crop salt-tolerance. In other words, N application above an optimum level under non-saline conditions did not increase crop yield. They also pointed out that the interactive nature of salinity and other stresses negatively/positively affecting nutrient availability, uptake and distribution. These topics are highly complex in the absence of salinity while, the presence of salinity stress adds a new level of complexity to the mineral nutrition of crops. Interaction effect of irrigation and salinity levels on maize was studied by Amer (2010). He reported that leaf temperature, transpiration rate and stomatal resistance of maize and also field water infiltration were significantly affected by irrigation and salinity levels and their interaction.

However, information on the interaction effect of irrigation requirement, salinity and N, are limited and needs to be known in the management of water, soil and crop. The objectives of this study were to evaluate the effect of salinity, irrigation and N levels on maize growth and yield grown in a semi-arid region of Iran on a silty clay loam soil.

Materials and Methods

Site description

This study was conducted in 2009 and 2010 at the Bajgah Agricultural Experiment Station located at 29°56’ N, 52°02’ E and 1810 m above the mean sea level, in southwest of Iran with a semi-arid climate. Long-term mean air temperature, precipitation and relative humidity of the region are 13.4 °C, 387 mm and 52.2%, respectively. Soil of the experimental site is classified as silty clay loam for 0.60 m of top soil profile. Physico-chemical properties of the soil are presented in Table 1. Chemical analysis of the fresh and saline irrigation water is also shown in Table 2.

Reference evapotranspiration (ET_o) in the study area was calculated using modified FAO-Penman-Monteith method (Razzaghi and Sepaskhah, 2012) with collected meteorological data in a standard weather station at the Agricultural College located nearby the experimental field. Mean daily air temperature (T_{avg}), relative humidity (RH_{avg}) and ET_o during growing period in 2009 and 2010 are shown in Figure 1. Potential evapotranspiration of maize (ET_c) calculated by multiplying ET_o and modified crop coefficient (K_c) in the study area (Shahrokhnia and Sepaskhah, 2013).

Table 1. Physico-chemical properties of the soil used in the experiment (average of two years).

Characteristic	Amount	
Depth (cm)	0-30	30-60
Texture	SCL*	SCL
% Clay	52.5	53.8
%Silt	33.0	34.5
Field capacity (-0.03 MPa) (%)	31	30
Permanent wilting point (-1.5 MPa) (%)	18	19
Bulk density (Mg m^{-3})	1460	1560
EC (dS m^{-1})	0.65	0.55
pH (saturated past)	7.50	7.45
Organic matter (%)	0.7	0.5
Total Nitrogen (%)	0.021	0.009
NO_3-N (mg L^{-1})	4.6	6.0
Available P (mg L^{-1})	21.0	11.0
Available K (mg L^{-1})	343.0	315.0

* Silty clay loam.

Table 2. Chemical analysis of the fresh and saline irrigation water used in the experiment (average of two years).

Characteristic	Fresh water	Saline water	
EC (dS m^{-1})	0.60	2.00	4.00
pH	7.80	7.70	7.80
Cl^{-1} (meq L^{-1})	1.81	17.27	40.37
Na^{+} (meq L^{-1})	1.74	18.9	30.3
Ca^{2+} (meq L^{-1})	2.15	16.17	39.41
Mg^{2+} (meq L^{-1})	2.00	2.00	2.00
HCO_3^{-} (meq L^{-1})	1.97	4.99	4.64

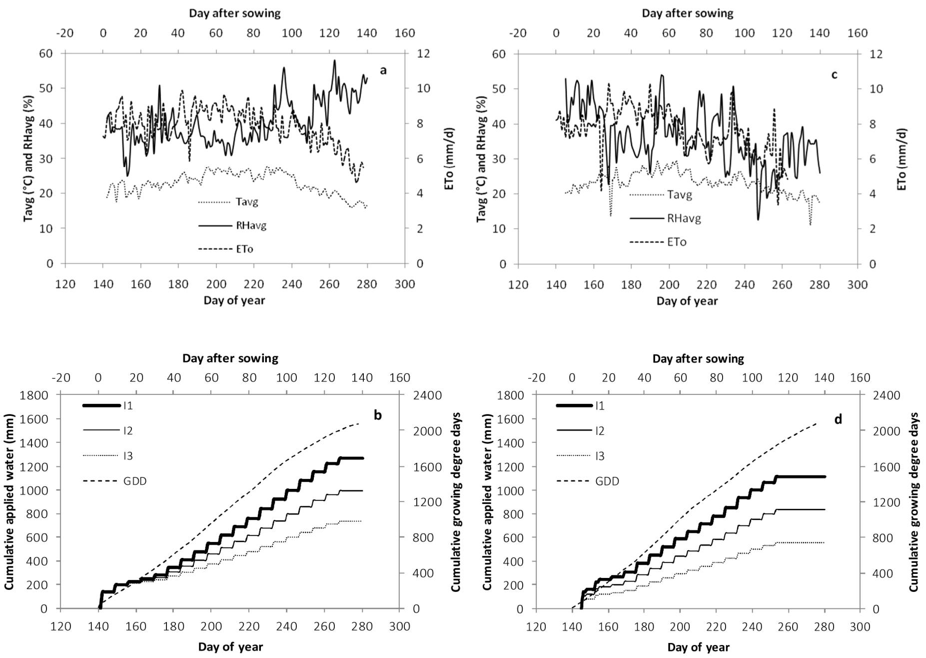


Figure 1. Daily mean air temperature (T_{avg}), relative humidity (RH_{avg}) and reference evapotranspiration (ET_o) during growing period in 2009 (a) and 2010 (c); cumulative applied water for different irrigation treatments ($1.25ET_c$: I_1, $0.75I_1$: I_2, $0.5I_1$: I_3) and cumulative growing degree day (GDD) in 2009 (b) and 2010 (d).

Experimental design and treatments

Maize (cv SC704, a late maturity hybrid) was planted on May 21, 2009 and May 25, 2010 using furrow irrigation system. The length and spacing of furrows were 5 and 0.75 m, respectively and there were five furrows in each plot. Final maize density after thinning was 88888 plants ha^{-1} with inter-row spacing of 15 cm. There was no precipitation or groundwater contribution (groundwater depth was > 40 m) during the growing seasons. Phosphorus in the form of triple superphosphate was applied at a rate of 200 kg ha^{-1} before planting.

The field was adequately watered (as 200 mm) in first and second irrigation (three-leaf stage of plant). After first irrigation a 1.5 m length aluminum access tube was installed at the center of the plots in two replications for measuring soil water content using neutron scattering method. Salinity and irrigation treatments were initiated at the third irrigation (3-4 leaf stage of maize). The treatments were three levels of irrigation water, salinity of irrigation water and nitrogen fertilizer rate. Irrigation was scheduled with 7-day interval (Sepaskhah et al., 1993; Zand-Parsa and Sepaskhah, 2001) and ET_c was considered as full plant water requirement for upcoming 7-day. Irrigation treatments were I_1 ($1.0ET_c$ $+0.25ET_c$ as leaching fraction), I_2 ($0.75I_1$) and I_3 ($0.5I_1$). Nitrogen (as urea) levels were 300, 150 and 0 kg N ha^{-1} as N_3, N_2 and N_1, respectively. Seventy percent of the urea fertilizer was applied at 3rd week and the rest was applied at 10th week after planting in both years. Salinity treatments were denoted S_3, S_2 and S_1, equivalent to 4, 2 and 0.6 (groundwater salinity) dS m^{-1}. The S_3 and S_2 treatments were obtained by adding NaCl and $CaCl_2$ salts to the irrigation water with equal proportion. Cumulative applied water for different irrigation treatments are shown in Figure 1. The experimental design was a split-split plot arrangement with three replications. Water, salinity and nitrogen treatments were considered as the main-, sub- and sub-sub factor, respectively. Irrigation water was applied using a volumetric measuring device. After first year, the field was leached using two heavy irrigation events to reduce soil profile salinity during winter season. The arrangement of the experimental treatments in the field in second year (2010) was the same as that in first year.

Measurements and calculations

Volumetric soil water contents in different irrigation treatments were monitored by neutron scattering method (neutron meter, Model CPN, 503DR) up to 1.5 m depth with 0.30 m intervals before each irrigation. Plant height, leaf area index (LAI) and dry matter (DM, oven dried at 70 °C until constant weight) production were measured from 3-6 plants during the growing season at 30-day intervals. Simultaneously, soil samples of each 0.30 m increment up to 1.5 m depth, were taken, air dried and passed through 2 mm sieve for chemical analysis including electrical conductivity of soil saturation extract (EC_e) using the methods described by the U. S. Salinity Laboratory Staff (Richards, 1954). Development stages of plant in each treatments were also recorded using a standardized maize development stage system (Ritchie et al., 1992) and the date was recorded at which 50% or more of the maize plants in each plot reached the vegetative (VS) and reproductive (RS) stages as: planting time (PT), emergence stage (VE), tasseling stage (VT), silking stage (R_1) and physiological maturity stage (R_6). The analysis of maize growth and development was conducted as a function of growing degree days (GDD), which was calculated as follows:

$$GDD = \sum_{i=1}^{n} \left(\frac{T_{\max_i} + T_{\min_i}}{2} - T_b \right) \tag{1}$$

where T_{min} is the daily minimum air temperature at day i (°C), T_{max} is the daily maximum air temperature at day i (°C), T_b the base temperature (°C) assumed as 8 °C for maize (Kiniry, 1991) and n is the number of days.

Plants were harvested on October 11 in both years from three middle rows of each plot with 4 m length and oven dried afterward at 70 °C until constant weight. Total DM and grain yield (GY, at 15 % moisture content) were measured. Nitrogen contents of grain and stover were determined by the Kjeldahl method (Chapman and Pratt, 1961). Harvest index (HI, as GY/DM), average weight of one ear (EW) and 1000-grain weight (1000-GW) were also determined. Water productivity (WP_{GY} and WP_{DM}) of each plot was calculated as DM or GY divided by irrigation water applied. By using the total N uptake of grain and stover and the amount of applied N as fertilizer, the apparent N recovery for different N treatments were calculated as follows:

$$NR = \frac{N_{ui} - N_{uc}}{N_{fi} - N_{fc}} \tag{2}$$

where NR is the apparent N recovery, N_{ui} and N_{uc} are the total N uptake of grain and stover for different N treatments and control, respectively (kg ha^{-1}) and N_{fi} and N_{fc} are the applied N as fertilizer for different N treatments and control, respectively (kg ha^{-1}). Further, by using the applied N as fertilizer and grain yield, the nitrogen use efficiency (NUE) for different N treatments was calculated as follows:

$$NUE = \frac{Y_i - Y_c}{N_{fi} - N_{fc}} \tag{3}$$

where Y_i and Y_c are the grain yield in different N treatments and control, respectively (kg ha^{-1}).

Besides, the GY behavior under interaction effect of irrigation, salinity and nitrogen was described by quadratic equations and contour (iso-quant) lines. Furthermore, the relationship between relative GY [the ratio of GY in treatments with water and nitrogen stress (GY_a) to its maximum (GY_m)] and average root-zone salinity of soil saturation extract (EC_e) was determined by regression analysis as fallows (Mass and Hoffman, 1977):

$$\frac{GY_a}{GY_m} = 1 - b(EC_e - EC_{threshold}) \qquad (4)$$

where $EC_{threshold}$ is the threshold value of EC_e and b is the growth reduction coefficient of maize GY. Furthermore, the EC_e for threshold ($EC_{threshold}$), 50% GY reduction and b were determined for each treatment.

Statistical analysis

The statistical analysis of collected data was carried out using MSTAT-C software. Measured data were analyzed by analysis of variance (ANOVA). Duncan´s method was used to find out the differences among means with significant level of 5% ($P \leq 0.05$) after testing the normality and homogeneity of variance for data. There was no significant effect of year on measured parameters. Therefore, two years mean values of the parameters were considered in the analysis.

Results and Discussion

The planting date in 2010 was 4 days later than 2009. As a result, the length of growing season was 138 days in 2009 and 134 days in 2010. There were 19 and 18 irrigation events with a total amount of 1266 and 1112 mm of applied water for I_1 treatment in 2009 and 2010, respectively (Figure 1). T_{avg} and RH_{avg} of growing season were 22.9 °C and 40.4% in 2009 and 23.2 °C and 36.3% in 2010. Soil salinity of the field in 2010 was slightly more than that in 2009; however, it was still below the maize threshold ($EC_{threshold}$=1.7 dS m^{-1}, Mass and Hoffman, 1977). The plants treated with saline water were shorter and showed old leaf chlorosis symptoms especially at latter period of the growing season. The main effect of experimental factors on all measured parameters were significant (P=0.05). Triple interaction of water, salinity and nitrogen was only significant on the DM, GY and NR.

Crop development stages

Development was clearly retarded by the drought and especially salinity treatments, since the maize growth advanced to specific vegetative and reproductive stages later in the drought and saline treatments when compared to control (Figure 2), e.g. the maize reached the silking stage 4 to

9 days and 5 to 29 days earlier in well watered and non-saline treatments, respectively. The duration for the VS was much higher in saline treatments (from 54.4% in I_1S_2 to 71.7% in I_3S_3) than that in no saline treatments. In general, maize under water and salinity stress had longer vegetative stage period by 11 and 16%, respectively. In this study the period from planting date to seedling emergence was the same for all treatments (7 day), because in this period the treatments still had not been initiated. These results confirmed growth-promoting water conditions as stated by Cakir (2004) and also observed by Yi et al. (2010) for rain-fed maize plant.

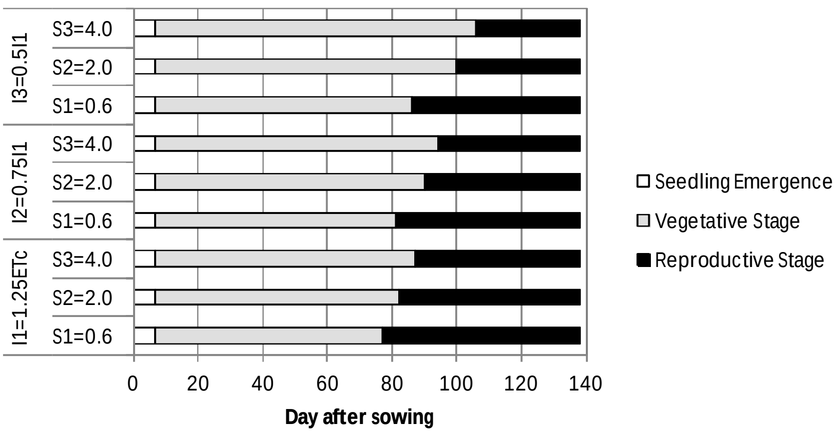


Figure 2. Duration (2-years average) of the seedling emergence, vegetative stage (from seedling emergence to silking) and reproductive stage (from silking to physiological maturity) of maize under different irrigation and salinity (dS m^{-1}) treatments.

Irrigation, salinity and nitrogen effects

Plant height and leaf area index

Plant height and LAI significantly increased and decreased with increasing irrigation and salinity levels, respectively (Table 3). Similar effect was observed on plant height for different nitrogen levels, whereas, there was no significant difference between maize height at 150 and 300 kg N ha^{-1}. These two measured parameters of maize were more affected by drought relative than salinity and N stress conditions, since, the LAI of maize reduced 34.9, 11.9 and 8.3% under water ($0.5I_1$), salinity (4 dS m^{-1}) and nitrogen (0 kg N ha^{-1}) stress, respectively. These values for plant height were also 29.8, 12.2 and 10.1%, respectively.

Dry matter, grain yield and harvest index

The main effect of irrigation, salinity and nitrogen and also the three-way interaction of irrigation (I) salinity (S) and nitrogen (N) were significant on DM and GY of maize ($P \leq 0.05$). DM and GY significantly increased with increasing water and nitrogen levels, whereas, increasing salinity levels of irrigation water significantly decreased DM and GY (Table 3). Maize produced less DM (36.6%) and GY (52.2%) under water stress conditions ($I_3=0.5I_1$ treatment) compared to the no water stress treatment ($I_1=1.25ET_c$). The corresponding values for salinity stress treatment ($S_3=4.0$ dS m^{-1}) were 18.4 and 22.5%, respectively relative to non-saline treatment ($S_1=0.6$ dS m^{-1}). While, the reduction percent in DM and GY in nitrogen stress treatment ($N_1=0$ kg N ha^{-1}) were 15.6 and 27.9%, respectively as compared to the highest application N rate ($N_3=300$ kg N ha^{-1}). There was a significant increase in HI with increasing irrigation levels. However, HI was statistically similar at water salinity levels of 2 and 4 dS m^{-1} and significantly lower relative to no salinity conditions. Furthermore, a similar result was obtained for HI under N treatments which it was not statistically different between 150 and 300 kg N ha^{-1}. GY reduction of maize under N stress (0 kg N ha^{-1}) was also reported as 61.6% compared to the highest N rate (300 kg N ha^{-1}) by Tafteh and Sepaskhah (2012).

Triple interaction effect of experimental factors on DM and GY is presented in Table 4. Results showed that DM and GY significantly increased by increasing the N application under non-saline irrigation water and for each irrigation level. Whereas, application of saline water under I_1 and I_2 irrigation levels significantly increased DM and GY with lower N level (150 kg N ha^{-1}) and then significantly decreased (except for DM under I_1S_2 treatment) at higher N rate (300 kg N ha^{-1}). These results indicate that DM and GY of maize showed a quadratic type response to N application rate under saline irrigation water with each irrigation treatments. This indicates that the optimum level of N will be less than 300 kg ha^{-1} in these conditions. As a result, N requirement for maize under saline irrigation water was lower (between 150-300 kg N ha^{-1}) as compared to non-saline water application.

The maximum amounts of both DM and GY was obtained at non-saline water application with $I_1=1.25ET_c$ irrigation levels and N application rate of 300 kg ha^{-1} (Table 4). While, the minimum amounts was obtained at the highest salinity level with no N application and under drought stress ($I_3=0.5I_1$ treatment).

Table 3. Effect of Irrigation, salinity levels and nitrogen application rates on maximum plant height (H), maximum leaf area index (LAI), final dry matter (DM), grain yield (GY), ear weight (EW), 1000-grain weight (1000-GW), harvest index (HI), water productivity for DM (WP_{DM}) and GY (WP_{GY}), nitrogen use efficiency (NUE), and apparent nitrogen recovery (NR) of maize.

Crop trait	Irrigation levels			Salinity levels (dS m^{-1})			Nitrogen application rates (kg ha^{-1})		
	I_1=1.25ET_c	I_2=0.75I_1	I_3=0.50I_1	S_1=0.6	S_2=2	S_3=4	N_1=0	N_2=150	N_3=300
H (cm)	212.8^{a*}	172.8^b	149.4^c	190.0^a	178.2^b	166.8^c	165.4^b	185.5^a	184.0^a
LAI	5.07^a	3.88^b	3.30^c	4.36^a	4.05^b	3.84^c	3.89^c	4.11^b	4.24^a
DM (Mg ha^{-1})	19.86^a	16.93^b	12.60^c	18.22^a	16.31^b	14.87^c	14.59^b	17.53^a	17.29^a
GY (Mg ha^{-1})	9.86^a	7.72^b	4.71^c	8.61^a	7.24^b	6.44^c	5.89^b	8.24^a	8.17^a
EW (g ear^{-1})	139.3^a	110.2^b	67.3^c	121.7^a	103.6^b	91.5^c	84.7^b	116.4^a	115.7^a
1000-GW (g)	191.4^a	166.6^b	157.0^c	180.6^a	169.2^b	165.2^b	159.6^b	177.3^a	178.0^a
HI	0.49^a	0.45^b	0.37^c	0.46^a	0.43^b	0.42^b	0.39^b	0.45^a	0.46^a
WP_{DM} (kg m^{-3})	1.67^c	1.90^b	2.12^a	2.10^a	1.88^b	1.71^c	1.69^b	2.01^a	1.99^a
WP_{GY} (kg m^{-3})	0.83^b	0.86^a	0.79^c	0.96^a	0.81^b	0.71^c	0.66^b	0.91^a	0.90^a
NUE (kg kg^{-1})	16.33^a	11.70^b	5.32^c	10.06^a	11.51^a	11.78^a	-	15.05^a	7.19^b
NR (kg kg^{-1})	0.43^{ab}	0.46^a	0.32^b	0.35^a	0.41^a	0.45^a	-	0.44^a	0.37^b

*Means in each row under irrigation, salinity and nitrogen levels for different traits followed by the same letter are not statistically different at $P \leq 0.05$ by Duncan's multiple range test.

Table 4. Interaction effect of irrigation, salinity levels and nitrogen application rates on final dry matter (DM), grain yield (GY), water productivity for GY (WP_{GY}) and nitrogen use efficiency (NUE) of maize.

Nitrogen application rate (kg ha^{-1})	Irrigation levels								
	I_1=1.25ET$_c$			I_2=0.75I_1			I_3=0.50I_1		
	N_1=0	N_2=150	N_3=300	N_1=0	N_2=150	N_3=300	N_1=0	N_2=150	N_3=300
Salinity levels (dS m^{-1})		DM (Mg ha^{-1})							
S_1=0.6	19.53^{cd}	21.74^{b}	23.52^{a}	17.01^{fg}	18.65^{de}	21.77^{b}	13.16^{jk*}	13.78^{ij}	14.81^{hi}
S_2=2	17.21^{efg}	21.36^{b}	20.66^{bc}	15.45^{h}	18.51^{def}	16.22^{gh}	11.80^{k}	12.95^{jk}	12.66^{jk}
S_3=4	14.75^{hi}	21.22^{b}	18.78^{de}	12.42^{jk}	17.36^{efg}	15.01^{hi}	9.95^{l}	12.18^{jk}	12.14^{k}
		GY (Mg ha^{-1})							
S_1=0.6	9.17^{e}	11.76^{b}	13.11^{a}	7.48^{fg}	8.79^{e}	10.50^{cd}	4.76^{lm}	5.69^{jk}	6.26^{ij}
S_2=2	7.15^{gh}	10.70^{c}	10.03^{d}	6.16^{ij}	9.06^{e}	8.13^{f}	4.00^{n}	5.07^{kl}	4.83^{lm}
S_3=4	6.13^{ij}	9.97^{d}	8.74^{e}	4.90^{l}	7.87^{f}	6.63^{hi}	3.22^{o}	4.38^{lmn}	4.14^{mn}
		WP_{GY} (kg m^{-3})							
S_1=0.6	0.77^{jkl}	0.99^{cde}	1.10^{b}	0.83^{hij}	0.98^{cdef}	1.18^{a}	0.80^{ijk}	0.95^{defg}	1.05^{bc}
S_2=2	0.59^{no}	0.90^{gh}	0.84^{hij}	0.69^{lm}	1.01^{cd}	0.91^{efgh}	0.67^{mn}	0.85^{hi}	0.81^{ijk}
S_3=4	0.51^{p}	0.91^{fgh}	0.83^{hij}	0.54^{op}	0.88^{ghi}	0.74^{klm}	0.54^{op}	0.73^{klm}	0.70^{lm}
		NUE (kg kg^{-1})							
S_1=0.6	-	17.26^{cd}	13.13^{de}	-	8.71^{ef}	10.08^{ef}	-	6.18^{fg}	4.99^{fg}
S_2=2	-	23.68^{ab}	9.60^{ef}	-	19.30^{bc}	6.57^{fg}	-	7.15^{fg}	2.76^{g}
S_3=4	-	25.57^{a}	8.71^{ef}	-	19.78^{bc}	5.76^{fg}	-	7.78^{fg}	3.07^{g}

*Means within each plant parameter followed by the same letter are not statistically different at $P \leq 0.05$ by Duncan's multiple range test.

1000-grain weight and ear weight

The values of EW and 1000-GW of maize significantly increased with increasing levels of irrigation as 106.9 and 21.9 %, respectively (Table 3). No significant differences were observed in EW and 1000-GW with N application. However, their values with N application rate of 300 kg N ha^{-1} were 36.6 and 11.5% higher than those values in no N application rate, respectively. There was also no significant effect on 1000-GW between irrigation salinity levels of 2 and 4 dS m^{-1}. Whereas, maize EW was statistically different between two salinity levels of irrigation water (i.e. 2.0 and 4.0 dS m^{-1}). However, the highest level of salinity (4.0 dS m^{-1}) caused a reduction of 24.8 and 8.5%, respectively in EW and 1000-GW of maize relative to no saline condition.

Water productivity for dry matter and grain yield

Dry matter and grain yield-based water productivity (WP_{DM} and WP_{GY}) under irrigation, salinity and nitrogen treatments is presented in Table 3. The values of WP_{GY} were less than unity in all treatments. WP_{DM} was statistically higher at lower levels of irrigation, whereas, WP_{GY} reached its maximum at irrigation level of I_2=0.75I_1. It is indicated that the optimum level of WP_{GY} could be achieved with saving some volume of irrigation water.

WP_{DM} and WP_{GY} significantly decreased with increasing salinity levels of irrigation water as 18.6 and 26%, respectively. N application resulted in higher WP for DM and GY. Furthermore, at N application rates of 150 and 300 kg N ha^{-1} WP_{DM} and WP_{GY} were not statistically different. Their values showed that the optimum WP for DM and GY might be obtained at N application of $<$300 kg N ha^{-1}. Tefteh and Sepaskhah (2012) also reported that N application rate of 200 kg N ha^{-1} is adequate for higher WP_{GY} compared to 300 kg N ha^{-1} maize is irrigated using alternate furrow irrigation system.

Triple interaction effect of experimental factors on WP_{GY} is presented in Table 4. Although there was no clear significant effect of triple interaction of I, S and N on WP_{GY}, however under salinity conditions maize had greater WP_{GY} at lower N application rate (150 kg N ha^{-1}). While, with fresh water application WP_{GY} significantly increased with increasing N application rate under each irrigation treatments. Similar result was reported by Tefteh and Sepaskhah (2012) for maize *cv* SC704. They also reported that under water shortage, higher WP obtained under lower N level (200 kg N ha^{-1}) relative to 300 kg N ha^{-1}. Their results are in accordance with our findings for WP under water deficit treatments (I_2 and I_3). The highest value of WP_{GY} was observed with fresh water application and 300 kg N ha^{-1} under I_2=0.75I_1 treatment as 1.18 kg m^{-3}. Genetic properties as well as environmental conditions influence the attainable highest value of WP_{GY}. The highest value of WP_{GY} for maize *cv* SC704 was reported as 0.872 kg m^{-3} by Tafteh and Sepaskhah (2012). Mansouri-far et al. (2010) reported WP_{GY} for a single cross *cv* of maize (SC647) up to 1.367 kg m^{-3} under different environmental conditions relative to the conditions of our study region.

Nitrogen use efficiency and apparent nitrogen recovery

NUE and NR are shown in Table 3. NUE statistically increased with increasing irrigation levels. There was significant difference between the NR of I_2 and I_3, while no significant difference was observed between I_1 and both I_2 and I_3. Salinity treatments had no significant effect on NUE and NR. NUE was statistically higher with lower N application rate (150 kg N ha^{-1}) relative to higher N level (300 kg N ha^{-1}), indicating that N supply might be exhausted by maize when its applied rate is low. While under higher application rate, some of N supply might be lost and then it is not efficient in production. Similar results were observed for NR. Our findings are in agreement with results reported by Tafteh and Sepaskhah (2012) for maize and Sepaskhah and Hosseini (2008) for wheat which stated that higher NUE and NR could be attained under lower N application rates (200 kg N ha^{-1}). Therefore, in term of NUE and NR, the N application rate of 150 kg N ha^{-1} is the optimum rate for the study region.

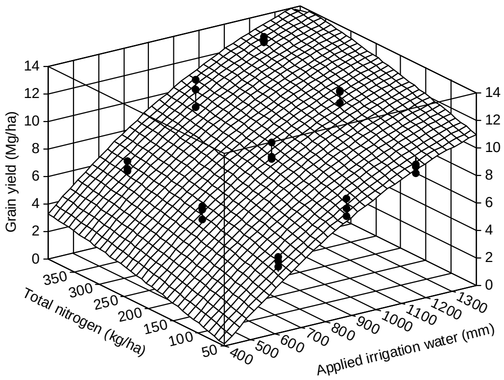
Triple interaction effect of experimental factors on NUE is presented in Table 4. There was no clear significant effect of triple interaction of I, S and N on NUE, however it is clear from Table 4 that at 300 kg N ha^{-1}, NUE decreased with saline irrigation water application, while a reverse trend was observed at lower N rate (150 kg N ha^{-1}). The causes arising from the fact that GY reduction was higher under salinity conditions at N levels of 0 and 300 compared to 150 kg N ha^{-1}. Furthermore, NUE in general decreased at N application rate of 300 kg ha^{-1} relative to 150 kg N ha^{-1}. In other words, the applied N in this rate was more than enough to produce the maximum yield. According to NUE, therefore, N application rate of 150 kg N ha^{-1}is the appropriate treatment especially under saline conditions.

Grain yield-water-salinity-nitrogen relationships

Grain yield-water-salinity-nitrogen function

Based on the above mentioned results, an ascending trend in maize GY was observed under no salinity conditions with increasing irrigation and nitrogen levels (Table 4). While, with application of saline water a quadratic type pattern was evident in GY with increasing N application rate, however it was not true for increasing irrigation levels. For maize GY production, yield surface functions were developed using multiple regression analysis at different salinity levels of irrigation water as a function of applied water and sum of applied and soil residual nitrogen. Results are presented in Figure 3 and Table 5. The shape of the surfaces in Figure 3 indicates that maize GY approached its maximum value under saline irrigation water. While, with fresh water maize GY tended to increase with increasing water and nitrogen application rate. Maximum GY under no saline conditions was calculated as 16.1 Mg ha^{-1} which would be achieved with 1762 mm of irrigation water and 750 kg ha^{-1} total nitrogen. Zand-Parsa and Sepaskhah (2001) reported that the maximum maize GY of 13.3 Mg ha^{-1} (for the same maize cultivar) could be attained with 1000 mm fresh irrigation water (EC=0.4 dS m^{-1}) and 212 kg N ha^{-1} in the study area under sprinkler irrigation. However, Majnooni-Heris et al. (2011) reported a maximum of 15.3 Mg ha^{-1} of GY for the same cultivar under irrigation level of 1.4 ET_c and 300 kg ha^{-1} N application rate. Our results seem to be unreasonable especially for N rate. This is attributed to the fact that a wide range of GY to irrigation and nitrogen levels has not been covered by the equation. Therefore, the extrapolation will not be accurate.

The maximum GY values at water salinity of 2.0 and 4.0 dS m^{-1} were 10.6 and 10.4 Mg ha^{-1}, respectively. These values would be achieved with 1304 and 1599 mm of irrigation water accompanying with 261 and 269 kg N ha^{-1}, respectively. The higher volume of irrigation water with salinity level of 4.0 dS m^{-1} was attributed to need for leaching requirement in these conditions.



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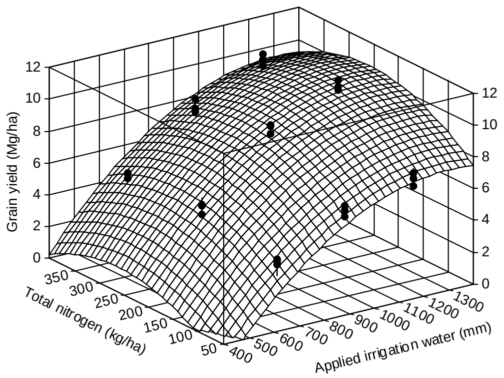

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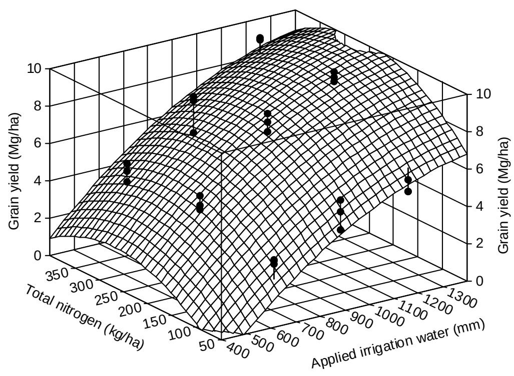

c

Figure 3. Grain yield surface as a function of applied irrigation water and total (applied and residual) nitrogen at different salinity levels: a=0.6, b=2.0 and c=4.0 dS m^{-1}.

Table 5. Multiple regression equations for maize grain yield (GY) as a function of applied irrigation water (I, mm) and applied and soil residual nitrogen (N, kg ha^{-1}) at different salinity levels with maximum achievable yield (GY_m) and optimum applied water (W_m) and applied and soil residual nitrogen (N_m).

Salinity level	Grain yield surface equation	GY_m (Mg/ha)	W_m (mm)	N_m (kg ha^{-1})
S_1=0.6 dS m^{-1}	$GY=-8.38+0.022I-6.25\times10^{-6}I^2+0.013N-8.84\times10^{-6}N^2$ $R^2=0.946$, SE=0.695, $p=1.18\times10^{-13}$, n=27	16.06	1762	750
S_2=2.0	$GY=-12.91+0.029I-1.11\times10^{-5}I^2+0.036N-6.93\times10^{-5}N^2$ $R^2=0.945$, SE=0.589, $p=1.47\times10^{-13}$, n=27	10.63	1304	261
S_3=4.0	$GY=-6.56+0.010I-4.73\times10^{-7}I^2+0.043N-8.25\times10^{-5}N^2$ $R^2=0.891$, SE=0.931, $p=5.93\times10^{-10}$, n=27	10.39	1599	269

Grain yield-water-salinity-nitrogen contour

Interaction effect of irrigation and salinity was not statistically significant on maize GY (P=0.05). Therefore, contour (iso-quant) plots were developed to show the combine effect of water and nitrogen on GY (Figure 4). The slope of the contour curves shows the magnitude of the response: an increase in the slope indicates a large effect of irrigation on the increase in GY for each N rate, while a decrease of the slope indicates a smaller effect of irrigation and larger effect of N on GY for each irrigation depth. The negative impact of deficit irrigation on GY was partially compensated by an increase in N application, while the negative impact of N stress on GY was compensated by an increase in irrigation depth (Figure 4). The simplest application of Figure 4 is the estimation of GY for each combination of irrigation depth and total N. For example, with seasonal available irrigation water of 800 mm, GY is nearly 6.5, 6.0 and 4.5 Mg ha^{-1} for an application of 100 kg N ha^{-1} at salinity levels of 0.6, 2.0 and 4.0 dS m^{-1} for irrigation water, respectively. Again with irrigation water of 800 mm, GY values for N application of 150 and 200 kg ha^{-1} are about 7.0, 6.5 and 5.5 and 7.1, 7.1 and 6.0 Mg ha^{-1} at irrigation salinity levels of 0.6, 2.0 and 4.0 dS m^{-1}, respectively. These results indicate that 50% increase of N application (i.e. 50 kg N ha^{-1}) caused an increase in GY of about 8, 8 and 22%, while a 100% increase of N application (i.e. 100 kg N ha^{-1}) resulted in an increase in GY of about 9, 10 and 33% at 0.6, 2.0 and 4.0 dS m^{-1} salinity levels of irrigation water, respectively. Thus, it is possible to make a decision on how much N fertilizer should be applied to maximize the benefits based on available water, the price of N fertilizer and irrigation water and the amount of final crop harvest. These results also showed that there is a quadratic response between maize GY and N application which agree with previous studies (Gheysari et al., 2009; Sheaffer et al., 2006).

There are many different combinations of irrigation depths and total N applied, resulting in different values for GY (Figure 4). It is evident from Figure 4a and negative slope zone in Figure 4 b and c that the amount of N that should be applied to compensate for a constant decrease (e.g. 50 mm) in irrigation water depth was higher at the deficit irrigation level as compared to full irrigation level. Similar results were reported by Gheysari et al. (2009) for silage maize. For each irrigation depth there was an optimum N application rate and any further increase in N did not result in a significant increase in GY (Figure 4a) and even it may lead to a decrease in GY value (positive slope zone of Figure 4b and c). This might be due to the fact that under saline water the higher N application rates may intensify the effect of salinity and finally resulted in yield reduction.

Grain yield-salinity function

Relationship between relative GY (GY_a/GY_m) and average root-zone salinity of soil saturation extract (EC_e) was determined for each treatment [Eq (4)] by regression analysis and the results are presented in Table 6 and Figure 5. The salinity indices including threshold EC_e, the EC_e for 50% GY reduction and the yield reduction coefficient for maize are showed in Table 6. These indices ranged between 1.31 to 2.56 dS m^{-1}, 2.6 to 5.30 dS m^{-1} and 12.3 to 54.8 % per dS m^{-1} for threshold EC_e, the EC_e for 50% GY reduction, and yield reduction coefficient for maize, respectively. Yield reduction coefficient by soil salinity for maize was also previously reported by Mass and Hoffman (1977) as 12.0 % per dS m^{-1} started at EC_e of 1.7 dS m^{-1}. Besides, Katerji et al. (2003) reported threshold EC_e and yield reduction coefficient for maize GY of 1.3 dS m^{-1} and 10.5% per unit soil salinity increase. Our results, in some cases, are in accordance or close to the results reported by Mass and Hoffman (1977) and Katerji et al. (2003). According to Table 6, threshold EC_e of maize GY increased with increasing N application rate under drought (I_3=0.5I_1) and well-watered (I_1=1.25ET_c) treatments. While, under I_2=0.75I_1 treatment threshold EC_e of maize GY increased at 150 kg N ha^{-1} application rate and then decreased at 300 kg N ha^{-1}. In other words, based on this index, maize is considered more tolerant to salinity with increasing N application under drought and well-watered conditions. However, based on the EC_e for 50% GY reduction, maize was more tolerant to salinity with application of 150 kg N ha^{-1} under each irrigation treatment. This is mainly due to the fact that the values of this salinity index at 150 kg N ha^{-1} were greater than those at 300 kg N ha^{-1}. The yield reduction coefficient for maize GY increased with increasing N application rate under drought stress (I_3=0.5I_1). These results indicated that the maize could be considered more sensitive to salinity under water stress conditions and it supports the fact that N-fertilization does not increase crop salt-tolerance (Grattan and Grieve, 1999). However, an inverse trend was observed in I_2=0.75I_1 treatment which maize had lower yield reduction coefficient at higher N application rate. At this irrigation level, maize is considered more tolerant to salinity with increasing N application rate and it confirms the fact that higher N requirement is needed for plant growth under higher soil water conditions (Sepaskhah and Tafteh, 2012). At well-watered treatment (I_1=1.25ET_c), yield reduction coefficient decreased at 150 kg N ha^{-1} and then increased at 300 kg N ha^{-1}. It means that maize could be considered more sensitive to salinity at the highest N application rate probably due to the additive effect of N to salinity.

Table 6. Threshold ECe, the EC_e for 50% yield reduction and yield reduction coefficient for maize grain yield at different irrigation levels and nitrogen application rates.

Nitrogen application rate (kg ha^{-1})	Irrigation levels		
	I_1=1.25ET_c	I_2=0.75I_1	I_3=0.50I_1
	Threshold EC_e (dS m^{-1})		
N_1=0	1.30	1.99	1.31
N_2=150	1.34	2.56	1.77
N_3=300	2.52	1.34	1.83
	EC_e for 50% yield reduction (dS m^{-1})		
N_1=0	1.30	3.35	2.60
N_2=150	1.34	4.16	2.79
N_3=300	2.52	4.00	2.74
	Yield reduction coefficient (% dS m^{-1})		
N_1=0	31.2	36.8	38.6
N_2=150	12.3	31.3	49.3
N_3=300	19.5	18.7	54.8

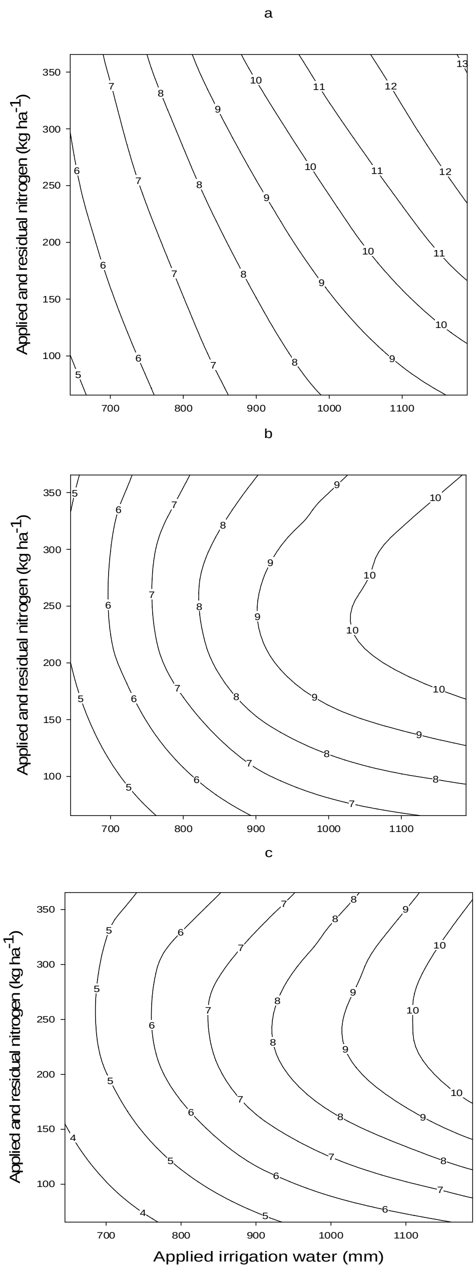

Figure. 4. Contour line of grain yield (Mg ha^{-1}) as a function of applied irrigation water and applied and residual nitrogen at different salinity levels: a=0.6, b=2.0 and c=4.0 dS m^{-1}.

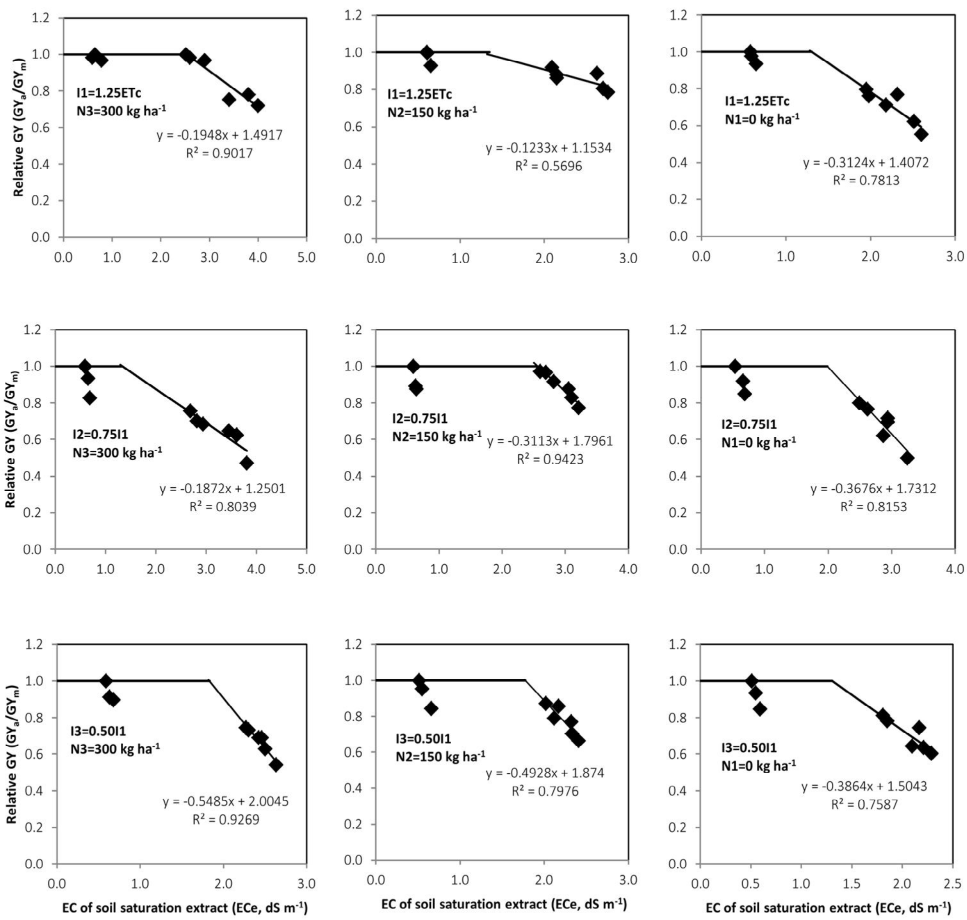

Figure. 5. Relationship between relative maize grain yield (GY_a /GY_m) and salinity of soil saturation extract (EC_e, dS m^{-1}) at different irrigation and Nitrogen levels.

Conclusions

Results of recorded development stages indicated that the vegetative growth stage had continued longer at water stress and especially salinity stress conditions. Furthermore, results indicated that all measured growth traits decreased under water, salinity and nitrogen stress, except WP_{DM} which had greater value under water stress conditions. The most susceptible parameters to water, salinity and nitrogen stress were GY followed by ear weight and LAI. Based on the GY, fresh water (EC_{iw}=0.6 dS m^{-1})

application at level of I_1=1.25ET_c with 300 kg N ha^{-1} was appropriate irrigation and N fertilizer management for maize production in the study region. According to WP results, application of unit volume of water was more efficient for GY under irrigation and N fertilizer management of I_2=0.75I_1 and 150 kg N ha^{-1} and also at no saline conditions. Based on NUE and NR, the N application rate of 150 kg N ha^{-1} was the optimum rate for the study region especially under saline conditions.

Our results also showed that maize GY could be presented as a function of applied irrigation and nitrogen levels at each salinity levels of irrigation water. These functions presented a quadratic type response under salinity conditions indicating lower need (<300 kg N ha^{-1}) for N supply. While, at no salinity stress conditions, a rising trend in GY versus applied irrigation and N was the predominant pattern. Further, the contour map of GY showed that there were many different combinations of irrigation depths and total N applied, resulting in different values for GY and an optimum point could be selected. Finally, the threshold EC_e, the EC_e for 50% GY reduction and yield reduction coefficient for maize obtained in this study showed that in general, maize did not tolerate salinity under higher N application rate (300 kg ha^{-1}), although in some cases its sensitivity to salinity decreased by increasing N application rate.

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