Reducing water and nitrogen inputs combined with plastic mulched ridge-furrow irrigation improves soil water and salt status in arid saline areas, China

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Abstract: Plastic mulched ridge-furrow irrigation is a useful method to improve crop productivity and decrease salt accumulation in arid saline areas. However, inappropriate irrigation and fertilizer practices may result in ecological and environmental problems. In order to improve the resource use efficiency in these areas, we investigated the effects of different irrigation amounts (400 (I1), 300 (I2) and 200 (I3) mm) and nitrogen application rates (300 (F1) and 150 (F2) kg N/hm^2) on water consumption, salt variation and resource use efficiency of spring maize (*Zea mays* L.) in the Hetao Irrigation District (HID) of Northwest China in 2017 and 2018. Result showed that soil water contents were 0.2%–8.9% and 13.9%–18.1% lower for I2 and I3 than for I1, respectively, but that was slightly higher for F2 than for F1. Soil salt contents were 7.8%–23.5% and 48.5%–48.9% lower for I2 than for I1 and I3, but that was 1.6%–5.5% higher for F1 than for F2. Less salt leaching at the early growth stage (from sowing to six-leaf stage) and higher salt accumulation at the peak growth stage (from six-leaf to tasseling stage and from grain-filling to maturity stage) resulted in a higher soil salt content for I3 than for I1 and I2. Grain yields for I1 and I2 were significantly higher than that for I3 and irrigation water use efficiency for I2 was 14.7%–34.0% higher than that for I1. Compared with F1, F2 increased the partial factor productivity (PFP) of nitrogen fertilizer by more than 80%. PFP was not significantly different between I1F2 and I2F2, but significantly higher than those of other treatments. Considering the goal of saving water and nitrogen resources, and ensuring food security, we recommended the combination of I2F2 to ensure the sustainable development of agriculture in the HID and other similar arid saline areas.

Keywords: plastic mulched ridge-furrow irrigation; crop water consumption; soil salt variations; resource use efficiency; Hetao Irrigation District

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1 Introduction

Soil salinity has become an important global environmental problem and poses a major threat to soil health, particularly in irrigated agricultural areas within the arid and semi-arid regions (Wei et al., 2020). Rational utilization of salinized land is of vital importance to ensure food security and to relieve pressures associated with population growth (Cheng et al., 2019). The Hetao Irrigation District (HID) in Northwest China is a typical salinization irrigation district with 160 mm annual precipitation and about 2240 mm high evaporation per year (Ren et al., 2016).

Maize (*Zea mays* L.) is one of the most important grain crops in the world and is a salt-sensitive species (Maas and Hoffman, 1983). The HID is one of the major spring maize production regions, and the planted maize area accounts for 35.6% of the total arable land area (Li et al., 2020). Irrigation water from the Yellow River is important for spring maize production here. Moreover, excessive irrigation and chemical fertilizer are frequently applied to obtain a high maize yield, which has resulted in various ecological and environmental problems, including excessive water consumption, soil salinity and losses of nitrogen and phosphorus (Sharma et al., 2005; Qadir et al., 2009; Zhao et al., 2014). An additional problem is that the amount of irrigation water diverted from the Yellow River to the HID will be reduced by 20% in the future (about 5×10^9 m^3/a) due to intensifying demands in the Yellow River basin (Zhang et al., 2016). Therefore, developing efficient water-saving irrigation and nitrogen fertilizer regimes is essential for the sustainability of agriculture, environment and ecosystem in the HID.

Plastic mulching is widely used to reduce water evaporation and soil heat loss, to inhibit the movement of salt to the soil surface, and to produce high and stable yields of crops in the HID (Zhang et al., 2011; Liu et al., 2014; Wang et al., 2015). The ridge-furrow mulching system is widely used in arid and semi-arid areas (Li and Gong, 2002; Zhou et al., 2009; Liu et al., 2014). Researchers have found that plastic mulched ridge-furrow irrigation can reduce soil evaporation, soil water and nitrogen percolation, increase crop yield and irrigation water use efficiency, and reduce salt accumulation on the surface of ridge compared with traditional flood/border irrigation (Bezborodov et al., 2010; Chen et al., 2015). Compared with micro sprinkler irrigation, plastic mulched ridge-furrow irrigation is easy to implement and the application cost is relatively low (Chen and Qi, 2013; Porhemmat et al., 2018). In addition, plastic mulched ridge-furrow irrigation is an effective method for enhancing fertilizer use efficiency (Zhang et al., 2018). Dong et al. (2018) suggested that plastic mulched ridge-furrow irrigation was effective for the crops in the HID, where precipitation is low and evaporation is high.

Soil water and salt transport processes are highly influenced by the amount of irrigation water applied (Phogat et al., 2018; Yuan et al., 2019). In addition, nitrogen fertilizer significantly affects the transport of soil water and salt (Dong et al., 2012; Zhang et al., 2012). Plants cannot fully utilize nutrients in saline environments because soil water and nitrogen absorption processes are greatly altered, thereby affecting plant metabolism (Dong et al., 2012). Thus, nitrogen use efficiency can be greatly affected by soil water and salinity, and proper application of nitrogen fertilizer and irrigation is considered to be one of the most important management practices to improve soil quality and to increase crop yields (Ella and Shalaby, 1993; Zhang et al., 2012). Meanwhile, uneven soil water and salt conditions caused by plastic mulched ridge-furrow irrigation is different from other irrigation systems (Guo et al., 2019). However, there are few data related to the water and salt regulation, and crop responses to different irrigation and fertilizer regimes under plastic mulched ridge-furrow irrigation in the HID.

Reducing the application of fertilizer in crops is considered for the food security. For example, nitrogen fertilizer application at about 60% of the conventional fertilizer rate was considered to be the best fertilizer strategy for both high grain yield and economic benefits when irrigation amount was sufficient (Bu et al., 2014; Mo et al., 2017; Wang et al., 2018). Nitrogen application rate of 135–180 kg N/hm^2 was considered to be the best fertilizer amount for sunflower in the HID (Zeng et al., 2014; Zhao et al., 2014). However, the responses of spring maize growth and grain yield to water consumption and salt variation are still unknown under the conditions of reducing irrigation amount and nitrogen fertilizer rate. A thorough comparison of reducing irrigation and fertilizer with conventional water and fertilizer application could provide information on the water use efficiency, salt variations and crop yield fluctuation. In this study, we hypothesized that half of the conventional nitrogen application rate (i.e., 150 kg N/hm^2) combined with an optimum irrigation amount could not only reduce crop water consumption and periodic fluctuation of soil salt, but also increase water and nitrogen efficiencies in the HID, China. Therefore, the main objectives of this study were to: (1) determine the impacts of irrigation and nitrogen regimes on soil water and crop water consumption characteristics under plastic mulched ridge-furrow irrigation; (2) study soil salt variations under different irrigation amounts and nitrogen application rates; and (3) analyze the interactive effects of water and nitrogen inputs on grain yield, PFP and water use efficiency.

2 Materials and methods

2.1 Study area

Field experiments were conducted at the Shuguang Experimental Station (40°46′N, 107°24′E; 1039 m a.s.l.), located in the west of the HID, Inner Mongolia Autonomous Region, China from April to September in 2017 and 2018. The study area belongs to an arid continental climate characterized by a low precipitation and a high evaporation. The mean annual precipitation is 105 mm, of which about 70%–80% occurs during the period from May to September (Wang et al., 2014). The annual mean temperature is 9.1°C and the potential evaporation is 2240 mm. The annual total sunshine duration ranges from 3100 to 3300 h, and the groundwater table is about 2.5 m. Soil physical and chemical properties at the study area are summarized in Table 1. Mean air temperature, rainfall and groundwater table during the study period are shown in Figure 1. Rainfall amounts were about 37 and 110 mm during the spring maize growing season in 2017 and 2018, respectively, indicating that 2017 was a relatively dry year and 2018 was a normal year (Yu et al., 2020). Distributions of temperature and rainfall differed greatly between the two growing seasons, potentially leading to different results.

Table 1 Soil physical and chemical properties of the study area

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Soil texture	Bulk density (g/cm^3)	Field capacity (g/g)	EC (dS/m)	pH
0–20	20.00	51.49	28.72	Silt loam	1.36	0.23	1.15	8.65
20–40	23.85	50.29	25.86	Silt loam	1.48	0.24	2.04	8.41
40–60	21.62	32.12	46.26	Silt loam	1.39	0.29	0.94	8.55
60–80	2.51	4.24	93.25	Sand	1.44	0.30	0.80	8.68
80–100	6.93	14.67	78.40	Sandy loam	1.47	0.29	0.73	8.65

Note: EC, electric conductivity.

2.2 Experimental design and field management

This experiment used completely randomized block design with six treatments and three replicates. High, moderate and low irrigation amounts were 400 (I1), 300 (I2) and 200 mm (I3), respectively. High (F1) and low fertilizer (F2) rates were 300 and 150 kg N/hm^2, respectively. The dates and amounts of three irrigations applied in 2017 and 2018 are shown in Table 2. The six treatments were high water and high fertilizer (I1F1), high water and low fertilizer (I1F2), moderate water and high fertilizer (I2F1), moderate water and low fertilizer (I2F2), low water and high fertilizer (I3F1), and low water and low fertilizer (I3F2). The 300 kg N/hm^2 total N application rate for high fertilizer was conducted as follows. Before sowing, the base fertilizer was used uniformly followed by the rotary tillage. Base fertilizer (total 150 kg N/hm^2) applications of diammonium phosphate (18.0% N content) and urea (46.4% N content) were 600 and 91 kg/hm^2, respectively, before planting and mulching in both years. The remaining 150 kg N/hm^2 was evenly applied of urea at the grain-filling stage in both years, and the topdressing was applied through broadcasting followed by the irrigation. The low fertilizer application was

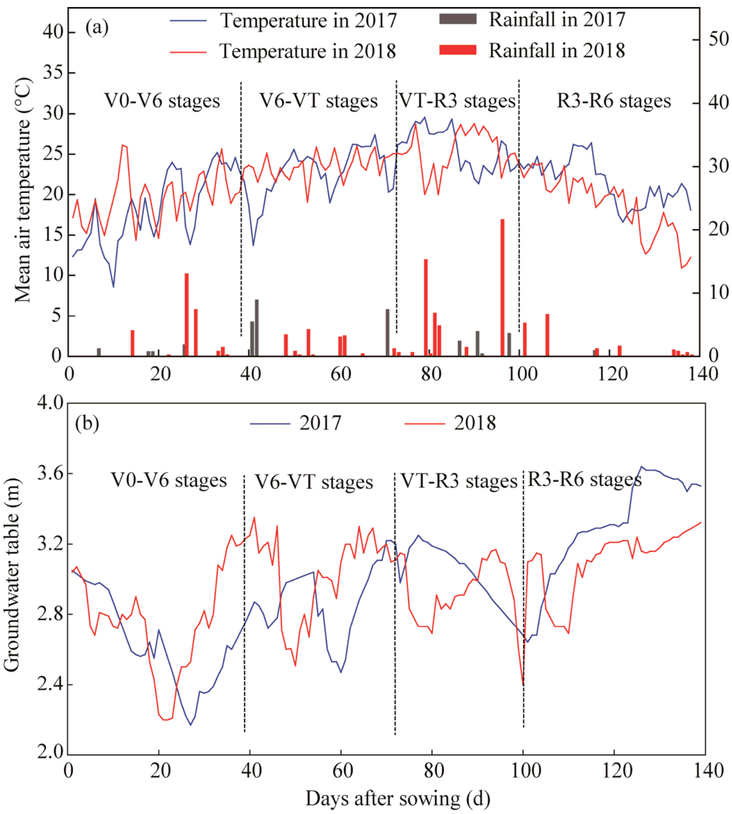

Fig. 1 Mean air temperature, rainfall (a) and groundwater table (b) during growing seasons in 2017 and 2018. V0, sowing stage; V6, six-leaf stage; VT, tasseling stage; R3, grain-filling stage; R6, maturity stage.

Table 2 Irrigation date and amount in the experiment

Growth stage of spring maize	Date in 2017	Date in 2018	I1 (mm)	I2 (mm)	I3 (mm)
V6	31 May	28 May	100	80	60
V12	2 July	30 June	100	75	50
R1	29 July	29 July	100	75	50
R3	17 August	18 August	100	70	40
Total			400	300	200

Note: I1, I2 and I3 are irrigation treatments. V6, six-leaf stage; V12, twelve-leaf stage; R1, silking stage; R3, grain-filling stage.

total 150 kg N/hm^2 that was the same with the base fertilizer of high fertilizer application. Irrigation water was obtained from a groundwater well. The average electrical conductivity (EC) of groundwater was 1.76 dS/m. Irrigation water was delivered by a pump equipped with a water meter.

The experimental field was divided into 12-m long plots consisting of three ridges and furrows. Ridges were 50 cm wide (20 cm high) and furrows were 70 cm wide (20 cm deep). After all ridges were mulched with plastic film, two rows of maize were planted on each ridge with 40 cm distance between rows and plants spaced 30 cm apart. Seeds of the maize cultivar "Ximeng 6" were planted by hand at a depth of 5 cm using a manual hole-planting machine on 25 April 2017 and 3 May 2018. Harvest occurred on 10 September 2017 and 11 September 2018. Daily meteorological parameters, including rainfall and temperature, were monitored from the meteorological observation station located approximately 150 m from the experiment (Fig. 1).

2.3 Sampling and measurement

2.3.1 Soil water and salt

Soil water content was measured approximately every 7 d at 10 and 20 cm depth and at 20-cm intervals from 20 to 120 cm depth using a Soil Moisture Profile Measurement System (TRIME-PICO-IPH TDR, Germany) that was installed in the center of the ridge and furrow at each plot. Soil samples were also collected by auger on the top of the ridge and the bottom of the furrow at 10-cm intervals from 0 to 20 cm depth and at 20-cm intervals from 40 to 100 cm depth before and after each irrigation event. Soil samples were air-dried and sieved through a 1-mm mesh screen for preparing dilute soil extract solutions. We measured soluble salt content (dS/m) with a conductivity meter based on extracts with a 1:5 soil:water ratio ($EC_{1:5}$).

The $EC_{1:5}$ was converted to salt content (S_t, g/kg) using the relationship presented by Tong et al. (2015):

$$S_t = 3.7657 \times EC_{1:5} - 0.2405 . \tag{1}$$

Soil salt storage (SSS, t/hm^2) was calculated as follows:

$$SSS = \sum \left(S_{ti} \times D_i \times l_i / 10 \right), \tag{2}$$

where S_{ti} is the salt content at the i soil layer (g/kg); D_i is the soil bulk density (g/cm^3); and l_i is the soil depth (cm).

2.3.2 Plant measurements

Ten maize plants were selected in each plot at harvest to determine yield components, including grain yield and thousand kernel weights (TKW). Thirty plants per treatment were sampled owing to three replications. Yield of each treatment was the mean value of three replicates.

2.3.3 Evapotranspiration (ET)

We calculated the water consumption for the whole growing season, i.e., ET (mm) based on the water balance formula:

$$ET = \Delta W + P + I - R - Q, \tag{3}$$

where ΔW is the change in soil water storage (mm); P and I are the rainfall (mm) and irrigation (mm), respectively; R is the surface runoff (mm); and Q is the soil water exchange at the depth of 100 cm, negative values indicate water flow upward from soil deeper than 100 cm to above it, and positive values indicate percolation at 100 cm depth (mm). R was assumed to be negligible as there was no observed runoff of irrigation water during the two growing seasons.

Maize roots are mainly distributed in the 0−100 cm soil depth under surface irrigation conditions (Wang et al., 2013), thus the 100-cm soil depth is considered to be the depth at which soil water flows into or out of the root zone. To calculate the soil water flux, we converted the water contents at intervals of 0–10, 10–20, 20–40, 40–60, 60–80, 80–100 and 100–120 cm to volumetric water content using the bulk densities listed in Table 1.

Soil water exchange (Q) in the 100 cm soil depth was determined using Darcy's equation (Ma et al., 2011; Liu et al., 2017):

$$Q = -K(\theta)\left(\frac{d\varphi}{dz} + 1\right) = -K(\theta)\left(\frac{\varphi_{110} - \varphi_{90}}{z_{110} - z_{90}} + 1\right), \tag{4}$$

$$K(\theta) = K_s S_e^{1/2} \left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2 , \tag{5}$$

$$S_e = \left(1 + \left(\alpha \left|\varphi_m\right|\right)^n\right)^{1/m} , \tag{6}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} , \tag{7}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity (cm/d); d is the partial derivative; φ_{100} and φ_{90} are the soil matric potentials at 110 cm and 90 cm (kPa), respectively; Z_{110} and Z_{90} are the soil water contents (cm^3/cm^3) at 110 cm and 90 cm, respectively; K_s is the saturated hydraulic conductivity (K_s=198 cm/d); S_e is the effective saturation; φ_m is the pressure head (cm); α, n and m are the empirical coefficients, which were 0.042, 0.0431 and 2.008, respectively (Dong et al., 2018); θ is the measured soil water content (cm^3/cm^3); θ_r is the residual soil water content (cm^3/cm^3); and θ_s is the saturated soil water content (cm^3/cm^3).

Soil water content was converted to soil matric potential using Equations 5 and 6. Soil water characteristic curves were regressed using Run-time Enhancement of Trusted Computing software developed by U. S. Salinity Laboratory (https://www.epa.gov/water-research/retention-curve-retc-computer-program). Soil water exchange was estimated daily using measured and interpolated data. As stated earlier, soil water content was measured approximately every 7 d. There was no great variation for soil water content in the 0−120 cm soil depth because of the low rainfall amounts and the controlled irrigation depths. Therefore, soil water content on days between two measurements was linearly interpolated using the two measured soil water contents (Liu et al., 2017).

2.3.4 Index calculation

Water consumption coefficient (K_{wc}) was calculated as the water consumption during a special growth stage (ET_{cs}, mm) divided by ET:

$$K_{wc} = \frac{ET_{cs}}{ET}. \tag{8}$$

Salt variation coefficient (K_{vc}) was calculated as the variation of soil salt storage in the 0−100 cm soil depth during a special growth stage (SSS_p, t/hm^2) divided by the variation of soil salt storage in the 0−100 cm soil depth during the whole growth stage (SSS_w, t/hm^2):

$$K_{vc} = \frac{SSS_p}{SSS_w}. \tag{9}$$

Positive values of SSS_p and SSS_w mean salt accumulation and negative values mean desalination.

Water use efficiency (WUE, kg/(hm^2·mm)) was calculated as grain yield (Y, kg/hm^2) divided by ET (mm):

$$WUE = \frac{Y}{ET}. \tag{10}$$

Irrigation water use efficiency (IWUE, kg/(hm^2·mm)) was calculated as Y (kg/hm^2) divided by irrigation amount (I, mm):

$$IWUE = \frac{Y}{I}. \tag{11}$$

Partial factor productivity (PFP, kg/kg) of nitrogen fertilizer was calculated as Y (kg/hm^2) divided the total amount of nitrogen fertilizer applied (F, kg/hm^2).

$$PFP = \frac{Y}{F}. \tag{12}$$

2.4 Statistical analysis

Analysis of variance (ANOVA) was conducted with SPSS software (IBM, Inc., USA). Multiple comparisons of mean values were performed using Duncan's multiple range test at a significance level of 0.05. All data analysis and graphing were performed using Excel 2016 (Microsoft, Inc., USA) and Sigmaplot v12.0 (Systat Software, Inc., USA).

3 Results

3.1 Soil water content and crop ET

Soil water content was higher at the seedling stage than at late growth stage for all treatments (Fig. 2). Soil water content at late growth stage in 2018 (Fig. 2c and d) was higher and fluctuated more than that in 2017 (Fig. 2a and b) because of higher rainfall during the non-irrigated periods in 2018. Mean soil water contents for I2 and I3 were 8.9% and 18.1%, respectively, lower than that for I1 in 2017, and 0.2% and 13.9% lower than that for I1 in 2018, respectively. But soil water content for I2 was higher than that for I1 at late growth stage in 2018 (Fig. 2c). In addition, soil water content for F2 was slightly higher than that for F1 in the two study years (Fig. 2b and d).

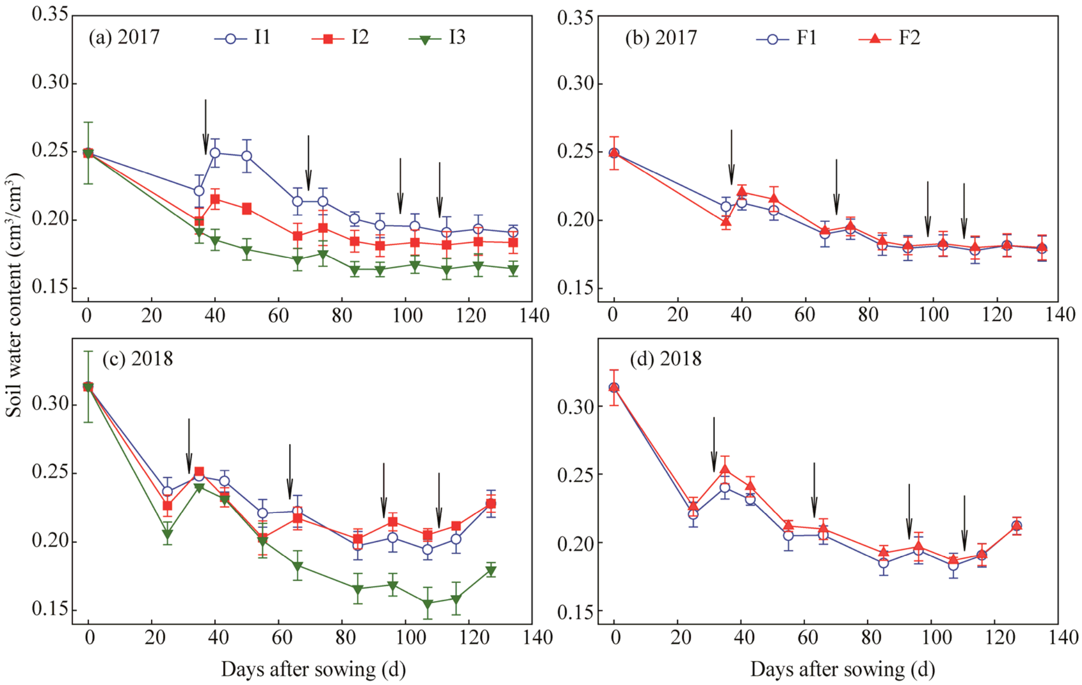

Fig. 2 Soil water contents in the 0–100 cm soil depth for different irrigation and fertilizer treatments during the growing seasons in 2017 (a and b) and 2018 (c and d) . I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. Arrows indicate irrigation dates. Bars indicate standard deviations.

Seasonal water flux in the 100 cm soil depth ranged from −1.3 to 37.9 mm in 2017 and −16.6 to 97.2 mm in 2018 (Table 3). The water flux was close to zero for I2F1 and I2F2, indicating 300 mm irrigation amount is enough for the ET of spring maize. Soil water percolation in the 100 cm soil depth increased with the increase in irrigation amount. High water percolation amounts for I1 indicated that spring maize was over-irrigation with 400-mm irrigation amount, especially in the relatively normal rainfall in 2018. Soil water variation from the day before sowing to the

Table 3 Water flux, soil water variation and ET in 2017 and 2018

Year	Treatment	Irrigation (mm)	Water flux (mm)	Soil water variation (mm)	ET (mm)
2017	I1F1	400	35.5	47.2	449^a
	I1F2	400	37.9	48.6	448^a
	I2F1	300	0.2	56.9	394^b
	I2F2	300	3.5	57.2	391^b
	I3F1	200	–1.3	62.4	301^c
	I3F2	200	–1.3	63.4	286^c
2018	I1F1	400	93.5	40.9	460^a
	I1F2	400	97.2	41.8	457^a
	I2F1	300	10.5	57.8	460^a
	I2F2	300	8.1	59.1	463^a
	I3F1	200	–16.6	60.1	389^b
	I3F2	200	–7.1	57.6	377^b

Note: I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. Water flux was the soil water flow at the 100 cm depth. Soil water variation is the soil water decreasing in the 0–100 cm soil depth during the growth season. ET, evapotranspiration. Values followed by different lowercase letters within the same column are significantly different among different treatments in the same year according to Duncan's multiple range test (P<0.05 level).

day after harvest ranged from 40.9 to 63.4 mm in the two growing seasons and decreased with the increase in irrigation amount. ET for I1 was significantly higher than those for I2 and I3, and the value for I2 was significantly higher than that for I3, but there was no significant difference in ET between two fertilizer treatments.

3.2 Water consumption coefficient (K_{wc}) and soil water exchange (Q)

Considering the actual sampling date and maize growth stages, we divided spring maize into four stages: V0-V6 (sowing to six-leaf stages), V6-VT (six-leaf to tasseling stages), VT-R3 (tasseling to grain-filling stages), and R3-R6 (grain-filling to maturity stages). K_{wc} reached the highest value at V6-VT stages, followed the order of V6-VT>R3-R6>VT-R3>V0-V6 (Table 4). K_{wc} increased with the increase in irrigation amounts and slightly affected by different nitrogen fertilizer rates. In general, K_{wc} was greater for I1 and I2 than for I3. In all treatments, the biggest K_{wc} occurred at V6-VT stages, reaching up to 0.36–0.37. Q in the 100 cm soil depth varied with the rainfall and irrigation amounts. When the irrigation water amount could not meet the crop water need, shallow groundwater may contribute to the crop growing and make up the shortage of water. In this study, deep percolation for I1 was remarkably higher than those for I2 and I3 at V0-V6 stages in 2017 and 2018. The deep percolation amounts for I1 were 24.6 and 26.4 mm higher than those for I2 and I3 in 2017, respectively, and 38.3 and 46.9 mm higher than those for I2 and I3 in 2018, respectively. During the experiment, the upward flux occurred at V6-VT and R3-R6 stages with ranges from 0.9 to 12.1 mm. The upward flux was greater for I3 than for I1 and I2, while Q for I1 was downward at V6-VT stages in 2018 and at R3-R6 stages in 2017 and 2018. Q for all treatments was downward at VT-R3 stages in the two study years, and the deep percolation amounts for I1F1 and I1F2 were remarkably higher than those of other treatments, especially in 2018 (Table 4).

Table 4 Water consumption (ET_{cs}), soil water exchange (Q) and water consumption coefficient (K_{wc}) of spring maize during different growth stages in 2017 and 2018

Year	Treatment	V0-V6 stages			V6-VT stages			VT-R3 stages			R3-R6 stages		
		ET_{cs} (mm)	Q (mm)	K_{wc}	ET_{cs} (mm)	Q (mm)	K_{wc}	ET_{cs} (mm)	Q (mm)	K_{wc}	ET_{cs} (mm)	Q (mm)	K_{wc}
2017	I1F1	63.5	30.8	0.141	166.5	–1.7	0.371	85.8	5.3	0.191	133.2	1.1	0.297
	I1F2	60.4	30.3	0.135	164.1	–0.9	0.366	87.1	7.2	0.194	136.4	1.4	0.304
	I2F1	55.0	5.2	0.140	146.0	–3.6	0.370	72.9	1.5	0.185	120.2	–2.9	0.305
	I2F2	52.1	6.8	0.133	144.8	–3.0	0.370	75.8	1.4	0.194	118.3	–1.6	0.303
	I3F1	41.2	4.2	0.137	112.3	–6.3	0.373	57.2	1.8	0.190	90.3	–1.1	0.300
	I3F2	37.2	4.0	0.130	105.7	–6.4	0.370	55.8	2.8	0.195	87.3	–1.8	0.305
2018	I1F1	68.8	40.9	0.150	170.6	11.3	0.371	84.4	19.3	0.183	136.0	22.0	0.296
	I1F2	66.4	46.0	0.145	165.6	10.4	0.362	89.8	21.9	0.197	135.2	18.9	0.296
	I2F1	60.8	13.3	0.132	165.6	–4.1	0.360	92.3	3.3	0.201	141.0	–2.0	0.307
	I2F2	62.3	11.0	0.135	168.9	–5.2	0.365	90.1	4.4	0.194	142.1	–2.2	0.307
	I3F1	55.9	3.7	0.144	141.4	–12.1	0.363	74.9	0.9	0.193	117.0	–9.1	0.301
	I3F2	53.2	3.4	0.141	139.9	–9.9	0.371	71.6	1.3	0.190	112.4	–2.0	0.298

Note: I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2; V0, sowing stage; V6, six-leaf stage; VT, tasseling stage; R3, grain-filling stage; R6, maturity stage.

3.3 Soil salt content

Because of the short interval between the third and fourth irrigations and more rainfall, soil samples before the fourth irrigation were not collected in 2018. Soil salt contents for I1 and I2 were noticeably lower than that for I3 during the two growing seasons (Fig. 3). Soil salt content for I3 fluctuated greatly before and after each irrigation event during the two growing seasons. Mean soil salt contents for I2 were 23.5% and 48.5% lower than those for I1 and I3, respectively, in 2017, and 7.8% and 48.9% lower in 2018 (Fig. 3a and c). Nitrogen fertilizer application rates had little influence on soil salt content (Fig. 3b and d). Soil salt contents for F1 were 1.6% and 5.5% higher than those for F2 in 2017 and 2018, respectively.

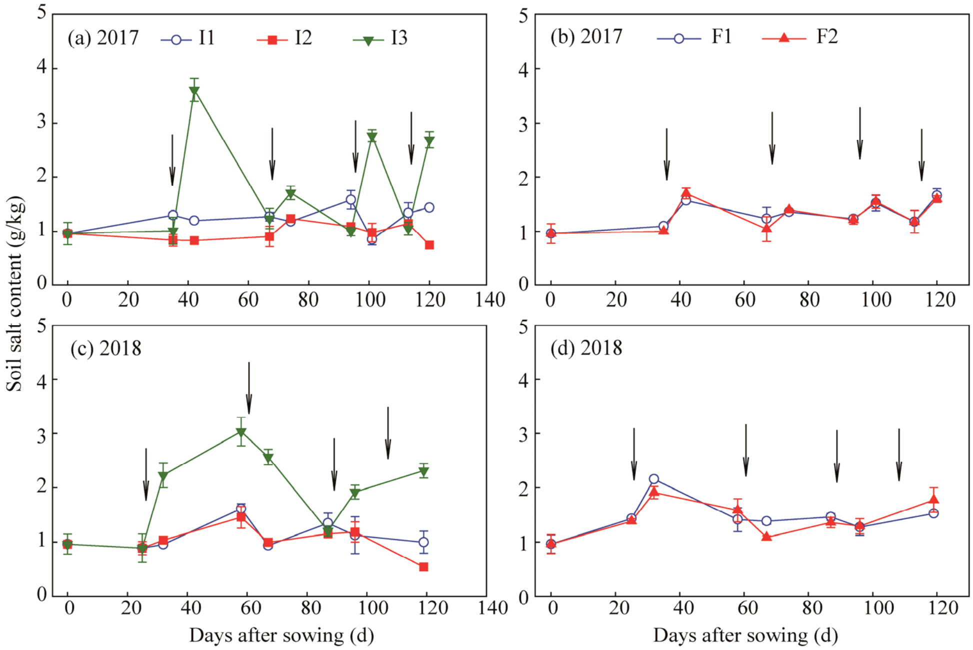

Fig. 3 Soil salt contents in the 0–100 cm soil depth for different irrigation and fertilizer treatments during the growing seasons in 2017 (a and b) and 2018 (c and d) . I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. Arrows indicate irrigation dates. Bars indicate standard deviations.

Soil desalination mainly occurred at V0-V6 stages, when crop water requirement was minimal and soil was the moistest (Table 5). Values of soil desalination for I1 and I2 were remarkably higher than that for I3, but there was little difference between F1 and F2. Soil salt accumulation mainly appeared at V6-R6 stages and salt accumulation for I2 was lower than those for I1 and I3. The variations of soil salt accumulation in the 0−100 cm soil depth were 7.9, 5.4, −2.0, −4.0, 23.4 and 25.2 t/hm^2 for I1F1, I1F2, I2F1, I2F2, I3F1 and I3F2 during the whole growing seasons in 2017, respectively, and 0.7, 0.3, −5.7, −6.4, 18.4 and 20.2 t/hm^2 in 2018. Because of the high SSS_p values for I3F1 and I3F2 at V0-R6 stages, the values of K_{vc} were lower than those of other treatments. While the values of K_{vc} for I1F1 and I1F2 were higher than those of other treatments in 2018, because of the lowest SSS_p values at V0-R6 stages.

3.4 Aboveground dry matter, yield and resource use efficiency

Aboveground dry matter accumulation of spring maize for each irrigation and fertilizer treatment combination during the two growing seasons in 2018 and 2018 was presented in Figure 4. In 2017, mean dry matter accumulation was 0.9% lower for F1 than for F2. I1 and I2 produced 36.6% and 44.1%, respectively, greater dry matter accumulation than I3 did. However, there was no difference in dry matter accumulation between the two fertilizer treatments under the same irrigation amount. Dry matter accumulation in 2018 presented the same trend as in 2017, but dry matter accumulation at late growth stage in 2018 was 11.9% higher than that in 2017. Dry matter accumulation for I2F2 was 31.7%–49.2% higher than those for I3F1 and I3F2 at late growth stage in 2017 and 2018. This result indicated that moderate irrigation amount and low fertilizer application rate (I2F2) could satisfy the water and nitrogen demands of spring maize growth.

Results of TKW, grain yield, WUE, IWUE and PFP are shown in Table 6. Grain yields were not significantly different among I1F1, I1F2, I2F1 and I2F2 in 2017 and 2018, but the values were significantly higher than those for I3F1 and I3F2. Grain yields for I1F2, I2F1, I2F2, I3F1 and I3F2 were 0.1%–36.2% lower than that for I1F1 in 2017 and −7.1%–18.1% lower in 2018. But grain yields were not significantly different between two fertilizer treatments for I1 and I2. Grain yield for I3F1 was significantly higher than that for I3F2 in 2017, but not in 2018. Thousand kernel weights for different treatments presented the similar trend as grain yield.

Table 5 Soil salt storage (SSS_w and SSS_p) and salt variation coefficient (K_{vc}) of spring maize during different growth stages in 2017 and 2018

Year	Treatment	V0-R6 stages	V0-V6 stages		V6-VT stages		VT-R3 stages		R3-R6 stages	
		SSS_w (t/hm^2)	SSS_p (t/hm^2)	K_{vc}	SSS_p (t/hm^2)	K_{vc}	SSS_p (t/hm^2)	K_{vc}	SSS_p (t/hm^2)	K_{vc}
2017	I1F1	7.9	–29.5	–3.7	12.1	1.5	16.3	2.1	9.1	1.1
	I1F2	5.4	–35.1	–6.5	11.3	2.1	17.7	3.3	11.5	2.1
	I2F1	–2.0	–30.8	15.4	9.1	–4.5	12.8	–6.4	6.9	–3.4
	I2F2	–4.0	–30.4	7.6	8.6	–2.1	11.3	–2.8	6.6	–1.6
	I3F1	23.4	–19.6	–0.8	13.5	0.6	21.1	0.9	8.5	0.4
	I3F2	25.2	–17.8	–0.7	12.6	0.5	21.0	0.8	9.4	0.4
2018	I1F1	0.7	–33.5	–47.9	11.2	16.0	14.6	20.9	8.4	12.0
	I1F2	0.3	–32.2	–107.3	10.7	33.3	12.9	40.4	8.6	27.9
	I2F1	–5.7	–29.1	5.1	7.9	–1.4	9.8	–1.7	5.7	–1.0
	I2F2	–6.4	–28.5	4.5	7.6	–1.2	8.1	–1.3	6.4	–1.0
	I3F1	18.4	–21.4	–1.2	12.8	0.7	19.6	1.1	7.5	0.4
	I3F2	20.2	–18.1	–0.9	11.8	0.6	18.8	0.9	7.8	0.4

Note: SSS_w, the variation of soil salt storage in the 0–100 cm soil depth during the whole growth stage; SSS_p, the variation of soil salt storage at a special growth period; K_{vc} was the ratio of SSS_p to SSS_w; I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. V0, sowing; V6, six-leaf stage; VT, tasseling stage; R3, grain-filling stage; R6, maturity stage.

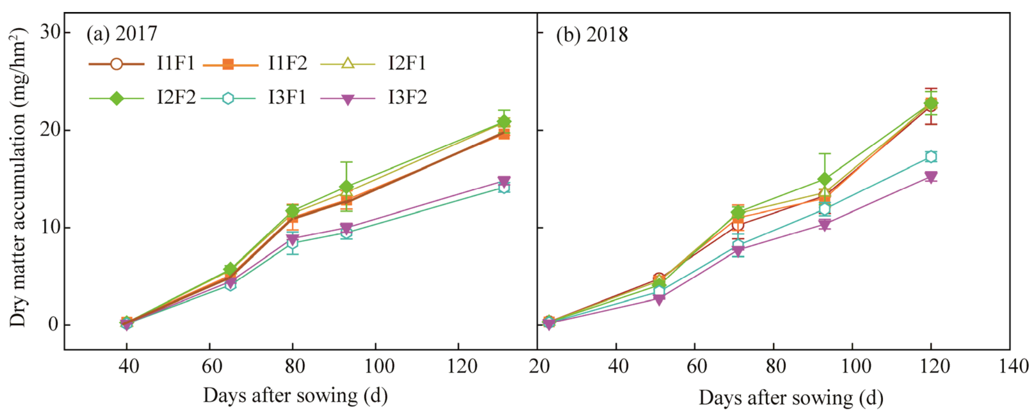

Fig. 4 Dry matter accumulation for each irrigation and fertilizer treatment combination during the growing seasons in 2017 (a) and 2018 (b). I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. Bars represent standard deviations.

WUE had no significant difference among different treatments. IWUE ranged from 36.4 to 61.4 kg/(hm^2·mm). The highest value of IWUE was found for I3F1. Grain yield was much lower in 2017 than in 2018 due to less rainfall in 2017. Therefore, IWUE was lower in 2017 than in 2018. No significant difference in IWUE was found between two fertilizer treatments. IWUE for I2 was higher than that for I1 in 2017 and significantly higher in 2018. IWUE was 14.7%–34.0% higher for I2 than for I1 in 2017 and 2018. Although IWUE was higher for I1, grain yield was significantly lower for I1 than for other treatments. PFP was significantly lower for F1 than for F2 in 2017 and 2018. Compared with F1, F2 increased PFP by more than 80%. PFP values for I1 and I2 were not significantly different, but the values were significantly higher than for I3 in 2017.

Table 6 Grain yield, water use efficiency (WUE), irrigation WUE (IWUE) and partial factor productivity (PFP) of nitrogen fertilizer of spring maize under different irrigation and nitrogen treatments in 2017 and 2018

Year	Treatment	TKW (g)	Grain yield (kg/hm^2)	WUE (kg/(hm^2•mm))	IWUE (kg/(hm^2•mm))	PFP (kg/kg)
2017	I1F1	374.5^a	14,678^a	32.7^a	36.7^b	62.4^{bc}
	I1F2	383.1^a	14,689^a	32.8^a	36.7^b	124.9^a
	I2F1	329.5^b	12,718^a	32.3^a	42.4^{ab}	54.1^{cd}
	I2F2	333.3^b	12,526^a	32.1^a	41.8^{ab}	106.5^a
	I3F1	309.5^b	10,275^b	34.0^a	51.4^a	43.7^d
	I3F2	274.4^c	9361^c	32.7^a	46.8^{ab}	79.6^b
2018	I1F1	377.4^a	14,550^a	31.6^a	36.4^c	61.8^c
	I1F2	383.0^a	15,521^a	34.0^a	38.8^c	132.0^a
	I2F1	371.8^a	14,646^a	31.9^a	48.8^b	62.3^c
	I2F2	370.6^a	15,589^a	33.6^a	52.0^b	132.6^a
	I3F1	358.4^b	12,272^b	31.5^a	61.4^a	52.2^c
	I3F2	353.8^b	11,930^b	31.6^a	59.7^a	101.4^b

Note: TKW, thousand kernel weights. I1, 400 mm irrigation; I2, 300 mm irrigation; I3, 200 mm irrigation; F1, 300 kg N/hm^2; F2, 150 kg N/hm^2. Values followed by different lowercase letters within the same column are significantly different among different treatments in the same year according to Duncan's multiple range test (P<0.05 level).

3.5 Response of maize growth to soil water and salt

The relationship between the increment of aboveground dry matter (IAGM) and K_{wc} was linear (R^2=0.94 in 2017 and R^2=0.89 in 2018; P<0.01), IAGM increased with increases in K_{wc} (Fig. 5a and b). The highest K_{wc} at V6-VT stages promoted the growth of maize. IAGM decreased with increases in soil salt content, thus the lower soil salt content is beneficial to maize growth (Fig. 5c and d). The relationship between grain yield and soil salt content was confirmed by the linear function (R^2=0.51 in 2017 and R^2=0.79 in 2018; P<0.01), i.e., grain yield decreased with increases in soil salt content (Fig. 6).

4 Discussion

4.1 Crop water consumption and soil salt content

The variations of soil water and salinity are highly influenced by the amount of irrigation applied, N fertilizer amounts also affects the transport of soil water and salt (Bu et al., 2014; Mo et al., 2017; Phogat et al., 2018; Yuan et al., 2019). The excessive nitrogen fertilizer application or over-irrigation will accelerate farmland salinization and damage water quality, resulting in a series of environmental problems (Sun et al., 2018; Li et al., 2020; Zou et al., 2020). Therefore, proper irrigation and fertilizer management is essential for the sustainable development of irrigation agriculture in the HID.

The distribution of soil water in field crops is mainly affected by irrigation, rainfall, atmospheric conditions and soil types. Due to low rainfall, uneven soil texture and atmospheric conditions in this area, the distribution of soil water is mainly affected by irrigation amount (Ren et al., 2016). Soil water changes among different treatments demonstrated that soil water decreased only slightly when irrigation was reduced by 25%. This may be related to deep percolation under high irrigation amount. Seasonal down-flux in the 100 cm soil depth (the positive value of water flux) for I1 was 36.7 and 92.9 mm in 2017 and 2018, respectively, but that was close to zero for I2 (Table 3). Soil water percolation in the 100 cm soil depth for I1 was close to 100 mm in 2018, thus soil water contents between I1 and I2 had little difference. Liu et al. (2017) reported similar results that soil water contents between 80% ET_c and 100% ET_c were much close, and their differences were smaller than those measured at early growth stage. Moreover, rainfall in 2018 was greater than in 2017, reaching up to 110 mm during the entire

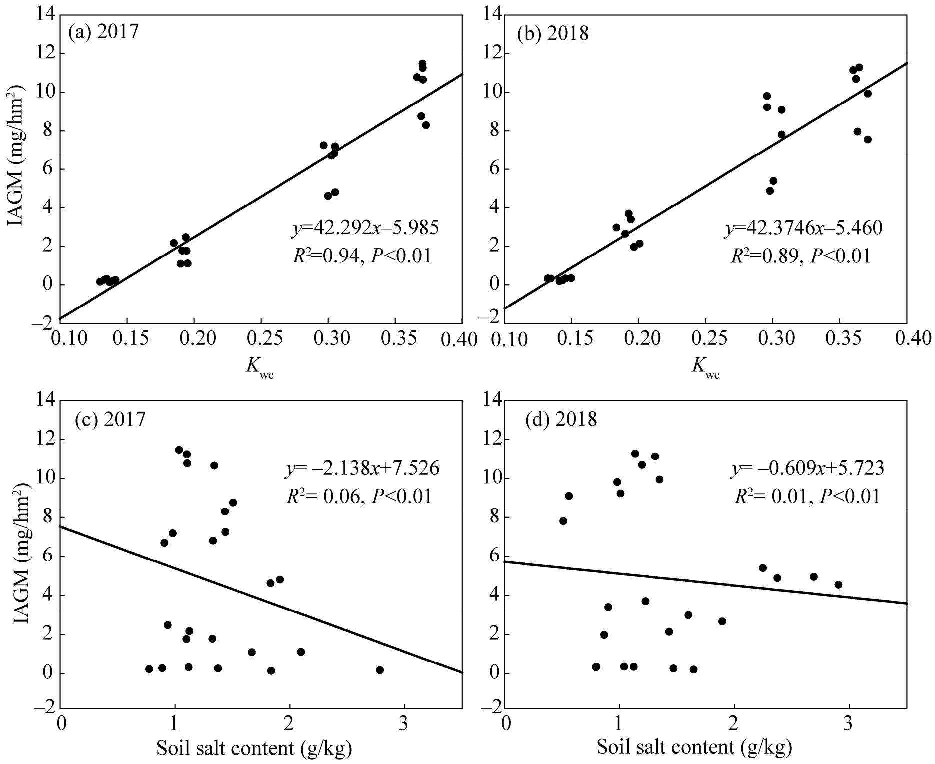

Fig. 5 Relationships of water consumption coefficient (K_{wc}; a and b) and soil salt content (c and d) with increment of aboveground dry matter (IAGM) in 2017 and 2018

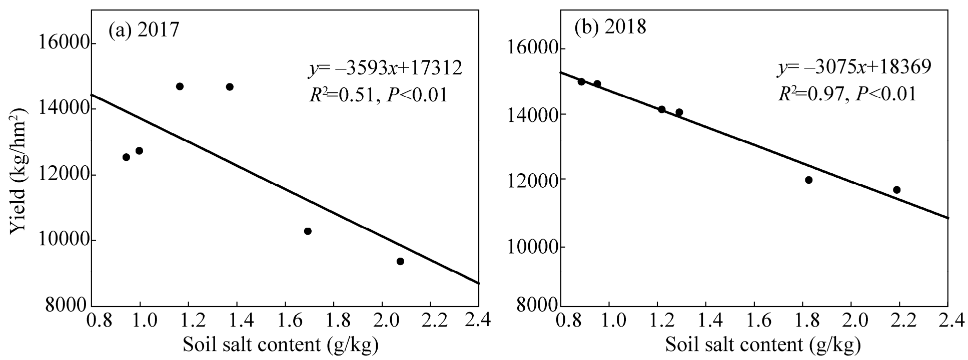

Fig. 6 Relationship between yield and soil salt content in 2017 (a) and 2018 (b)

maize growing season, thereby weakening the effects of deficit irrigation on soil water distribution to some extent. In this study, soil water content for F2 was slightly higher than that for F1, which may be related to the high water utilization for F1. The similar result was reported in the study of Xue et al. (2019).

In this study, the higher K_{wc} at V6-VT and R3-R6 stages, which occurred at the key water requirement periods of maize (Zhang et al., 2021), promoted the rapid plant growth and grain-filling (Ali et al., 2019). These results were in agreement with findings reported by Li et al. (2020b), who found that irrigation water allocation was higher at the maize growth stages in July and August than at other stages. Zhang et al. (2021) also reported the biggest K_{wc} was obtained at V6-VT stages, which was similar with this result. The main reason for the higher K_{wc} could be attributed to the vigorously vegetative growth and the longest duration of growth at this period. In arid region, irrigation is critical water resource for plant growth and yield production, and is also a major contribution to ET. Owing to the higher deep percolation for I1, the difference of ET between I1 and I2 was reduced, ET for I1 and I2 had no significant difference in 2018. This was consistent with Ning et al. (2021), who reported that crop evapotranspiration had little difference when irrigation amount ranged from 0.8 ET_c to 1.1 ET_c. ET_{cs} values for I1F1, I1F2, I2F1 and I2F2 were much higher than those for I3F1 and I3F2 (Table 4). Thus, maize growth and grain-filling were promoted, consequently produced a higher grain yield for I1F1, I1F2, I2F1 and I2F2.

Salt stress inhibits water uptake and results in the relatively low water consumption (Ben-Asher et al., 2006; Jiang et al., 2010). When irrigation occurs, salts move downward with irrigation water and upward with soil evaporation and plant transpiration. High irrigation amounts are more likely to result in a series of environmental problems, such as losses of nitrogen and phosphorus, and groundwater pollution (Sharma et al., 2005; Qadir et al., 2009). Furthermore, high irrigation amounts may lead to salt rebounding after the irrigation events (Mailhol et al., 2007). Previous study has showed that excessive irrigation amounts can result in the significant salt leaching (Feng et al., 2005) from vertical infiltration, and a large portion of water horizontally permeates ridges (Chen and Qi, 2013; Chen et al., 2015). After each irrigation event, a large amount of salt can leach to the deep soil layers (Phogat et al., 2018; Du et al., 2019). After a period of intense evaporation, salt may move upward to the surface soil layer (Devkota et al., 2015). In addition, shallow groundwater level in this area (Fig. 1b) may result in soil salt rebounding after the large amount of irrigation. In this study, both I1 and I2 presented good desalination effects, but soil salt was higher for I1 than for I2, especially in 2017, this may be related to salt rebounding. Owing to more rainfall during non-irrigation period, soil salt rebounding was alleviated, and there was little difference in soil salt contents between I1 and I2 in 2018 (Fig. 3b). Devkota et al. (2015) reported that reducing irrigation amount was conducive to minimizing secondary soil salinization. In our study, the weak effect of salt leaching accompanying with the large interval of soil sampling after each irrigation event resulted in the noticeably higher soil salt content for I3 than for I1 and I2 (Fig. 3a and c). In addition, salt leaching mainly occurred in the furrow and some salt might have conceivably been transported to the ridge through the furrow for 200 mm irrigation amount. Similar results were also reported (Rajak et al., 2006; Chen and Qi, 2013; Chen et al., 2015; Liu et al., 2016). Thus, high and moderate irrigation amounts produced a lower salt environment, which could be beneficial for the growth of spring maize (Ors and Suarez, 2017; Yang et al., 2019). Less salt leaching at early stages (V0-V6) and more salt accumulation in the peak water consumption stages (V6-R3) resulted in the higher soil salt storage for I3 than for I1 and I2 (Table 5). At V0-V6 stages, soil desalination was higher for I1F1, I1F2, I2F1 and I2F2 than for I3F1 and I3F2. At V6-R6 stages, soil salt accumulation was lower for I2 than for I1 and I3, because of the alleviated salt rebounding for I1 and the weak salt leaching for I3 (Chen and Qi, 2013; Devkota et al., 2015). Consequently, SSS_w for I2F1 and I2F2 were negative (desalination), and soil salt conditions were superior to other treatments at growth stages.

4.2 Crop responses to irrigation and N fertilizer

Generally, crop yield increases as irrigation and nitrogen fertilizer increase, but the yield cannot increase obviously with their further increase (Peña-Haro et al., 2009; Wang et al., 2018). As previously reported, researchers found that maize yield was quadratically correlated to irrigation and fertilizer amounts (Zou et al., 2020; Yan et al., 2021). Excessive nitrogen application may lead to overly strong nutrient uptake, delayed maturity and reduced production (Wang et al., 2018). Appropriate irrigation and reduced fertilizer had negligibly negative effects on grain yields (Jin et al., 2012; Paredes et al., 2014). This study found that the aboveground dry matter and grain yield had little differences between F1 and F2, but had much difference under different irrigation amounts. The little difference results between F1 and F2 confirmed our hypothesis that 150 kg N N/hm^2 is sufficient for spring maize under plastic mulched ridge-furrow irrigation. Dry matter accumulation for I2F2 was higher at late growth stages compared with the other treatments (Figs. 2 and 4). The better plant growth resulted in higher grain yield and IWUE for I2F2 in both years (Zhang et al., 2011), especially in 2018.

5 Conclusions

Reducing the high irrigation amount by 25% (300 mm) and reducing the conventional fertilizer amount by 50% (150 kg N/hm^2) increased soil moisture and improved soil salinity under plastic mulched ridge-furrow irrigation. With 300 mm irrigation amount and 150 kg N/hm^2 fertilizer amount achieved a comparable aboveground dry matter and grain yield as conventional management, while saved 25% water and 50% fertilizer. In addtion, reducing water and nitrogen inputs increased the partial factor productivity of nitrogen fertilizer and irrigation water use efficiency. Irrigation water use efficiency for 300 mm irrigation amonut was 14.7%–34.0% higher than that for high irrigation, and compared with conventional fertilizer, 150 kg N/hm^2 increased the partial factor productivity of nitrogen fertilizer by more than 80%. Therefore, plastic mulched ridge-furrow irrigation with 300 mm irrigation amount and 150 kg N/hm^2 fertilizer amount can be applied as a promising approach to improve resource use efficiencies and alleviate soil salinization in the HID. The results of this study provide guidelines for appropriate water and nitrogen management for spring maize production in the HID, especially in terms of comprehensively optimizing crop water consumption, soil salinity and grain yield.

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