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

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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/hm2) 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.

Full Text

Preamble

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 an effective method for improving crop productivity and reducing salt accumulation in arid saline areas. However, inappropriate irrigation and fertilizer practices may lead to ecological and environmental problems. To improve resource use efficiency in these regions, we investigated the effects of different irrigation amounts (400 mm (I1), 300 mm (I2), and 200 mm (I3)) and nitrogen application rates (300 kg N/hm^2 (F1) and 150 kg N/hm^2 (F2)) on water consumption, salt dynamics, and resource use efficiency of spring maize (*Zea mays* L.) in the Hetao Irrigation District (HID) of Northwest China during 2017 and 2018. Results showed that soil water contents were 0.2%-8.9% and 13.9%-18.1% lower for I2 and I3, respectively, compared with I1, but were 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, respectively, but were 1.6%-5.5% higher for F1 than for F2. Reduced salt leaching during early growth (from sowing to six-leaf stage) and greater salt accumulation during peak growth periods (from six-leaf to tasseling stage and from grain-filling to maturity stage) resulted in higher soil salt content for I3 compared with 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 was

significantly higher than in other treatments. Considering the goals of saving water and nitrogen resources while ensuring food security, we recommend the I2F2 combination to promote sustainable agricultural development in the HID and 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 a critical global environmental problem that poses a major threat to soil health, particularly in irrigated agricultural areas within arid and semi-arid regions [?, ?]. Rational utilization of salinized land is vital for ensuring food security and alleviating pressures associated with population growth [?, ?]. The Hetao Irrigation District (HID) in Northwest China is a typical salinized irrigation district with 160 mm annual precipitation and approximately 2240 mm of high annual evaporation [?, ?].

Maize (*Zea mays* L.) is one of the world' s most important grain crops and is a salt-sensitive species [?, ?]. The HID is a major spring maize production region, with maize plantings accounting for 35.6% of the total arable land area [?, ?]. Irrigation water from the Yellow River is crucial for spring maize production in this region. However, excessive irrigation and chemical fertilizer applications are frequently used to obtain high maize yields, resulting in various ecological and environmental problems, including excessive water consumption, soil salinization, and nitrogen and phosphorus losses [?, ?, ?, ?]. An additional challenge is that the amount of irrigation water diverted from the Yellow River to the HID will be reduced by 20% in the future (approximately 5$×10^{9}$ m^3/a) due to intensifying demands within the Yellow River basin [?, ?]. 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, inhibit salt movement to the soil surface, and produce high and stable crop yields in the HID [?, ?, ?, ?]. The ridge-furrow mulching system is commonly employed in arid and semi-arid areas [?, ?, ?, ?]. Researchers have found that plastic mulched ridge-furrow irrigation can reduce soil evaporation and soil water and nitrogen percolation, increase crop yield and irrigation water use efficiency, and decrease salt accumulation on ridge surfaces compared with traditional flood/border irrigation [?, ?, ?]. Compared with micro-sprinkler irrigation, plastic mulched ridge-furrow irrigation is easier to implement and has relatively lower application costs [?, ?, ?]. In addition, plastic mulched ridge-furrow irrigation is an effective method for enhancing fertilizer use efficiency [?, ?]. Dong et al. (2018) suggested that plastic mulched ridge-furrow irrigation was effective for 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 [?, ?, ?]. In addition, nitrogen fertilizer significantly affects soil water and salt transport [?, ?, ?]. Plants cannot fully utilize nutrients in saline environments because soil water and nitrogen absorption processes are greatly altered, thereby affecting plant metabolism [?, ?]. Thus, nitrogen use efficiency can be greatly affected by soil water and salinity, and proper application of nitrogen fertilizer and irrigation is considered one of the most important management practices for improving soil quality and increasing crop yields [?, ?, ?]. Meanwhile, uneven soil water and salt conditions caused by plastic mulched ridge-furrow irrigation differ from other irrigation systems [?, ?]. However, few data exist regarding water and salt regulation and crop responses to different irrigation and fertilizer regimes under plastic mulched ridge-furrow irrigation in the HID.

Reducing fertilizer application in crops is considered important for food security. For example, nitrogen fertilizer application at approximately 60% of the conventional rate was found to be the best fertilizer strategy for achieving both high grain yield and economic benefits when irrigation amounts were sufficient [?, ?, ?, ?]. A nitrogen application rate of 135–180 kg N/hm^2 was considered optimal for sunflower in the HID [?, ?, ?]. However, the responses of spring maize growth and grain yield to water consumption and salt variation remain unknown under conditions of reduced irrigation and nitrogen fertilizer rates. A thorough comparison of reduced irrigation and fertilizer practices with conventional water and fertilizer application could provide information on water use efficiency, salt variations, and crop yield fluctuations. 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) investigate 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.

2.1 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 western HID, Inner Mongolia Autonomous Region, China, from April to September in 2017 and 2018. The study area has an arid continental climate characterized by low precipitation and high evaporation. Mean annual precipitation is 105 mm, with approximately 70%–80% occurring from May to September [?, ?]. The annual mean temperature is 9.1°C, and potential evaporation is 2240 mm. 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 [Figure 1: see original paper].

Rainfall amounts were approximately 37 mm 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 [?, ?]. Distributions of temperature and rainfall differed greatly between the two growing seasons, potentially leading to different results.

2.2 Experimental Design and Field Management

This experiment used a completely randomized block design with six treatments and three replicates. High, moderate, and low irrigation amounts were 400 mm (I1), 300 mm (I2), and 200 mm (I3), respectively. High (F1) and low (F2) fertilizer 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 total N application rate of 300 kg N/hm^2 for the high fertilizer treatment was implemented as follows. Before sowing, base fertilizer was applied uniformly followed by rotary tillage. Base fertilizer applications (totaling 150 kg N/hm^2) of diammonium phosphate (18.0% N content) and urea (46.4% N content) were 600 and 91 kg/hm^2, respectively, applied before planting and mulching in both years. The remaining 150 kg N/hm^2 was evenly applied as urea at the grain-filling stage in both years, with topdressing applied through broadcasting followed by irrigation. The low fertilizer application totaled 150 kg N/hm^2, which was the same as the base fertilizer application in the high fertilizer treatment.

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 a meteorological observation station located approximately 150 m from the experiment (Fig. 1).

2.3.1 Soil Water and Salt

Soil water content was measured approximately every 7 days 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) installed in the center of the ridge and furrow in 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 (St, g/kg) using the relationship presented by Tong et al. (2015):

$$St = 0.2405 \times EC_{1:5} + 0.0214$$

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

$$SSS = \sum_{i=1}^{n} \frac{St_i \times D_i \times l_i}{10}$$

where St is the salt content at the i-th soil layer (g/kg), D is the soil bulk density (g/cm^3), and l 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 due to three replications. Yield of each treatment was the mean value of three replicates.

2.3.3 Evapotranspiration (ET)

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

$$ET = P + I - R - Q + \Delta W$$

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

Maize roots are mainly distributed in the 0–100 cm soil depth under surface irrigation conditions [?, ?], thus the 100-cm soil depth is considered the boundary at which soil water flows into or out of the root zone. To calculate soil water flux, we converted 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 [?, ?, ?]:

$$Q = -K(\theta)\frac{d\phi}{dz}$$

$$K(\theta) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$\phi_m = \frac{1}{\alpha}\left[\left(\frac{\theta_s - \theta_r}{\theta - \theta_r}\right)^{1/m} - 1\right]^{1/n}$$

where K( ) 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, Ks is the saturated hydraulic conductivity (Ks = 198 cm/d), Se is the effective saturation, ϕm is the pressure head (cm), α, n, and m are empirical coefficients (0.042, 0.0431, and 2.008, respectively) [?, ?], is the measured soil water content (cm^3/cm^3), r is the residual soil water content (cm^3/cm^3), and 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 the 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 noted earlier, soil water content was measured approximately every 7 days. There was no significant variation in soil water content in the 0–120 cm soil depth due to low rainfall amounts and controlled irrigation depths. Therefore, soil water content on days between measurements was linearly interpolated using the two measured values [?, ?].

2.3.4 Index Calculation

Water consumption coefficient (Kwc) was calculated as water consumption during a specific growth stage (ETcs, mm) divided by ET:

$$Kwc = \frac{ETcs}{ET}$$

Salt variation coefficient (Kvc) was calculated as the variation of soil salt storage in the 0–100 cm soil depth during a specific growth stage (SSSp, t/hm^2) divided by the variation of soil salt storage in the 0–100 cm soil depth during the whole growth stage (SSSw, t/hm^2):

$$Kvc = \frac{SSSp}{SSSw}$$

Positive values of SSSp and SSSw indicate salt accumulation, while negative values indicate desalination.

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

$$WUE = \frac{Y}{ET}$$

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

$$IWUE = \frac{Y}{I}$$

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

$$PFP = \frac{Y}{F}$$

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).

3.1 Soil Water Content and Crop ET

Soil water content was higher at the seedling stage than at the late growth stage for all treatments (Fig. 2 [Figure 2: see original paper]). Soil water content at the late growth stage in 2018 (Fig. 2c and d) was higher and fluctuated more than in 2017 (Fig. 2a and b) due to higher rainfall during non-irrigated periods in 2018. Mean soil water contents for I2 and I3 were 8.9% and 18.1% lower, respectively, than that for I1 in 2017, and 0.2% and 13.9% lower, respectively, than that for I1 in 2018. However, soil water content for I2 was higher than that for I1 at the late growth stage in 2018 (Fig. 2c). In addition, soil water content for F2 was slightly higher than that for F1 in both study years (Fig. 2b and d).

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 that 300 mm irrigation is sufficient for spring maize ET. Soil water percolation in the 100 cm soil depth increased with increasing irrigation amount. High percolation amounts for I1 indicated that spring maize was over-irrigated at the 400-mm irrigation amount, especially during the relatively normal rainfall year of 2018. Soil water variation from the day before sowing to the day after harvest ranged from 40.9 to 63.4 mm during the two growing seasons and decreased with increasing 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 the two fertilizer treatments.

3.2 Water Consumption Coefficient (Kwc) and Soil Water Exchange (Q)

Considering the actual sampling dates and maize growth stages, we divided spring maize growth into four stages: V0-V6 (sowing to six-leaf stage), V6-VT (six-leaf to tasseling stage), VT-R3 (tasseling to grain-filling stage), and R3-R6 (grain-filling to maturity stage). Kwc reached its highest value at the V6-VT stage, following the order V6-VT > R3-R6 > VT-R3 > V0-V6 (Table 4). Kwc increased with increasing irrigation amounts and was slightly affected by different nitrogen fertilizer rates. In general, Kwc was greater for I1 and I2 than for I3. In all treatments, the largest Kwc occurred at the V6-VT stage, reaching up to 0.36–0.37.

Q in the 100 cm soil depth varied with rainfall and irrigation amounts. When irrigation water amounts could not meet crop water needs, shallow groundwater may have contributed to crop growth and compensated for water shortages. In this study, deep percolation for I1 was remarkably higher than those for I2 and I3 at the V0-V6 stage in both 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, upward flux occurred at the V6-VT and R3-R6 stages, ranging 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 the V6-VT stage in 2018 and at the R3-R6 stage in both 2017 and 2018. Q for all treatments was downward at the VT-R3 stage in both study years, and the deep percolation amounts for I1F1 and I1F2 were remarkably higher than those of other treatments, especially in 2018 (Table 4).

3.3 Soil Salt Content

Due to the short interval between the third and fourth irrigations and additional 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 both growing seasons (Fig. 3 [Figure 3: see original paper]). Soil salt content for I3 fluctuated greatly before and after each irrigation event during both 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.

Soil desalination mainly occurred at the V0-V6 stage, when crop water requirement was minimal and soil was moistest (Table 5). Desalination values for I1 and I2 were remarkably higher than that for I3, but there was little difference between F1 and F2. Soil salt accumulation mainly occurred at the 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, respectively, during the entire 2017 growing season, and 0.7, 0.3, −5.7, −6.4, 18.4, and 20.2 t/hm^2 in 2018. Due to the high SSSp values for I3F1 and I3F2 at the V0-R6 stages, the Kvc values were lower than those of other treatments. In contrast, Kvc values for I1F1 and I1F2 were higher than those of other treatments in 2018 due to the lowest SSSp values at the 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 is presented in Figure 4 [Figure 4: see original paper]. In 2017, mean dry matter accumulation was 0.9% lower for F1 than for F2. I1 and I2 produced 36.6% and 44.1% greater dry matter accumulation, respectively, than I3. However, there was no difference in dry matter accumulation between the two fertilizer treatments under the same irrigation amount. Dry matter accumulation in 2018 showed the same trend as in 2017, but dry matter accumulation at the late growth stage in 2018 was 11.9% higher than in 2017. Dry matter accumulation for I2F2 was 31.7%–49.2% higher than those for I3F1 and I3F2 at the late growth stage in both 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 for 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 these 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. However, grain yields were not significantly different between the 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 showed similar trends as grain yield.

WUE showed no significant difference among treatments. IWUE ranged from 36.4 to 61.4 kg/($hm^2 \cdot mm$). The highest IWUE value 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 the 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 both years. 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 both years. Compared with F1, F2 increased PFP by more than 80%. PFP values for I1 and I2 were not significantly different, but were significantly higher than for I3 in 2017.

3.5 Response of Maize Growth to Soil Water and Salt

The relationship between the increment of aboveground dry matter (IAGM) and Kwc was linear ($R^2 = 0.94$ in 2017 and $R^2 = 0.89$ in 2018; $P < 0.01$), with IAGM increasing as Kwc increased (Fig. 5a [Figure 5: see original paper] and b). The highest Kwc at the V6-VT stage promoted maize growth. IAGM decreased with increasing soil salt content, indicating that lower soil salt content is beneficial for maize growth (Fig. 5c and d). The relationship between grain yield and soil salt content was confirmed by a linear function ($R^2 = 0.51$ in 2017 and $R^2 = 0.79$ in 2018; $P < 0.01$), i.e., grain yield decreased with increasing soil salt content (Fig. 6 [Figure 6: see original paper]).

4.1 Crop Water Consumption and Soil Salt Content

Variations in soil water and salinity are highly influenced by irrigation amount, and nitrogen fertilizer amounts also affect soil water and salt transport [?, ?, ?, ?, ?]. Excessive nitrogen fertilizer application or over-irrigation will accelerate farmland salinization and damage water quality, resulting in a series of environmental problems [?, ?, ?, ?]. Therefore, proper irrigation and fertilizer management is essential for sustainable development of irrigation agriculture in the HID.

Soil water distribution 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, soil water distribution is primarily affected by irrigation amount [?, ?]. Soil water changes among treatments demonstrated that soil water decreased only slightly when irrigation was reduced by 25%. This may be related to deep percolation under high irrigation amounts. Seasonal down-flux in the 100 cm soil depth (positive water flux values) for I1 was 36.7 and 92.9 mm in 2017 and 2018, respectively, but was close to zero for I2 (Table 3). Soil water percolation in the 100 cm soil depth for I1 approached 100 mm in 2018, thus soil water contents between I1 and I2 showed little difference. Liu et al. (2017) reported similar results, finding that soil water contents between 80% ETc and 100% ETc were very close, with differences smaller than those measured at early growth stages. Moreover, rainfall in 2018 was greater than in 2017, reaching up to 110 mm during the entire 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 higher water utilization for F1. Similar results were reported by Xue et al. (2019).

In this study, higher Kwc values at the V6-VT and R3-R6 stages, which occurred during key water requirement periods for maize [?, ?], promoted rapid plant growth and grain-filling [?, ?]. These results agree with findings by Li et al. (2020b), who reported that irrigation water allocation was higher during maize growth stages in July and August than at other stages. Zhang et al. (2021) also reported that the highest Kwc was obtained at the V6-VT stage, similar to our results. The main reason for higher Kwc could be attributed to vigorous vegetative growth and the longest duration of growth during this period. In arid regions, irrigation is a critical water resource for plant growth and yield production and is a major contributor to ET. Due to higher deep percolation for I1, the difference in ET between I1 and I2 was reduced, and ET for I1 and I2 showed no significant difference in 2018. This is consistent with Ning et al. (2021), who reported that crop evapotranspiration showed little difference when irrigation amount ranged from 0.8 ETc to 1.1 ETc. ETcs 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 producing higher grain yields for I1F1, I1F2, I2F1, and I2F2.

Salt stress inhibits water uptake and results in relatively low water consumption [?, ?, ?]. 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 environmental problems, such as nitrogen and phosphorus losses and groundwater pollution [?, ?, ?]. Furthermore, high irrigation amounts may lead to salt rebounding after irrigation events [?, ?]. Previous studies have shown that excessive irrigation amounts can cause significant salt leaching [?, ?] from vertical infiltration, with large portions of water horizontally permeating ridges [?, ?, ?]. After each irrigation event, substantial salt can leach to deep soil layers [?, ?, ?]. After periods of intense evaporation, salt may move upward to the surface soil layer [?, ?]. In addition, the shallow groundwater level in this area (Fig. 1b) may result in soil salt rebounding after large irrigation amounts. In this study, both I1 and I2 showed good desalination effects, but soil salt was higher for I1 than for I2, especially in 2017, which may be related to salt rebounding. Due to more rainfall during non-irrigation periods, 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, weak salt leaching combined with large intervals between soil sampling after each irrigation event resulted in noticeably higher soil salt content for I3 compared with I1 and I2 (Fig. 3a and c). In addition, salt leaching mainly occurred in the furrow, and some salt might have been transported to the ridge through the furrow at the 200 mm irrigation amount. Similar results have been reported [?, ?, ?, ?, ?]. Thus, high and moderate irrigation amounts produced a lower salt environment, which could benefit spring maize growth [?, ?, ?]. Less salt leaching at early stages (V0-V6) and more salt accumulation during peak water consumption stages (V6-R3) resulted in higher soil salt storage for I3 compared with I1 and I2 (Table 5). At the V0-V6 stage, soil desalination was higher for I1F1, I1F2, I2F1, and I2F2 than for I3F1 and I3F2. At the V6-R6 stages, soil salt accumulation was lower for I2 than for I1 and I3 due to alleviated salt rebounding for I1 and weak salt leaching for I3 [?, ?, ?]. Consequently, SSSw for I2F1 and I2F2 were negative (desalination), and soil salt conditions were superior to other treatments during growth stages.

4.2 Crop Responses to Irrigation and N Fertilizer

Generally, crop yield increases with irrigation and nitrogen fertilizer application, but yields cannot increase significantly with further increases [?, ?, ?]. As previously reported, researchers found that maize yield was quadratically correlated with irrigation and fertilizer amounts [?, ?, ?]. Excessive nitrogen application may lead to overly strong nutrient uptake, delayed maturity, and reduced production [?, ?]. Appropriate irrigation and reduced fertilizer had negligibly negative effects on grain yields [?, ?, ?]. This study found that aboveground dry matter and grain yield showed little difference between F1 and F2, but differed substantially under different irrigation amounts. The small differences between F1 and F2 confirmed our hypothesis that 150 kg 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 other treatments (Figs. 2 and 4). Better plant growth resulted in higher grain yield and IWUE for I2F2 in both years [?, ?], 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. The combination of 300 mm irrigation and 150 kg N/hm^2 fertilizer achieved comparable aboveground dry matter and grain yield as conventional management while saving 25% water and 50% fertilizer. In addition, reducing water and nitrogen inputs increased the partial factor productivity of nitrogen fertilizer and irrigation water use efficiency. Irrigation water use efficiency for the 300 mm irrigation amount 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 and 150 kg N/hm^2 fertilizer 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, particularly for comprehensively optimizing crop water consumption, soil salinity, and grain yield.

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Note: Figure translations are in progress. See original paper for figures.