

Article

Effects of Irrigation Water Salinity on Soil Properties, N₂O Emission and Yield of Spring Maize under Mulched Drip Irrigation

Chenchen Wei ¹, Fahu Li ¹, Peiling Yang ^{1,*}, Shumei Ren ¹, Shuaijie Wang ^{1,2}, Yu Wang ¹, Ziang Xu ¹, Yao Xu ¹, Rong Wei ¹ and Yanxia Zhang ^{1,3}

¹ College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China

² Henan Water Conservancy Survey, Ltd., Zhengzhou 450000, China

³ Gongnongqu Electric Pumping Station, Xigu District, Lanzhou 730060, China

* Correspondence: yangpeiling@126.com; Tel./Fax: +86-10-6273-7866

Received: 19 June 2019; Accepted: 24 July 2019; Published: 26 July 2019



Abstract: Brackish water has been widely used to irrigate crops to compensate for insufficient freshwater water supply for agricultural use. The goal of this research was to determine an efficient brackish water use method to increase irrigation efficiency and reduce N₂O emission. To this end, we conducted a field experiment with four salinity levels of irrigation water (1.1, 2.0, 3.5, and 5.0 g·L⁻¹ with drip irrigation) at Hetao Irrigation District (Inner Mongolia, China) in 2017 and 2018. The results show that irrigation with 3.5–5.0 g·L⁻¹ water salinity increased the soil salinity compared with irrigation using 1.1–2.0 g·L⁻¹ water salinity. The soil water content with 5.0 g·L⁻¹ brackish water irrigation was significantly higher than with 1.1–3.5 g·L⁻¹ water salinity due to the effect of salinity on crop water uptake. The overall soil pH increased with the increase in irrigation water salinity. Saturated soil hydraulic conductivity decreased with the increase in irrigation water salinity. These results indicate that brackish water irrigation aggravates the degree of soil salinization and alkalization. The soil N₂O cumulative flux resulting from irrigation with 5.0 g·L⁻¹ water salinity was 51.18–82.86% higher than that resulting from 1.1–3.5 g·L⁻¹ water salinity in 2017, and was 32.38–44.79% higher than that resulting from 1.1–2.0 g·L⁻¹ in 2018. Irrigation with brackish water reduced maize yield, and the reduction in yield in 2018 was greater than that in 2017, but irrigation with 2.0 g·L⁻¹ brackish water did not significantly reduce maize yield in 2017. These results suggest that reducing the salinity of irrigation water may effectively reduce soil N₂O emission, alleviate the degree of soil salinization, and increase crop yield.

Keywords: irrigation water salinity; soil salinization and alkalization; soil N₂O emission; maize yield; correlation relationship; Hetao Irrigation District

1. Introduction

Situated in Inner Mongolia, Hetao Irrigation District (HID) is an important commodity grain-producing area in Northwest China. Due to the region's arid climate, agricultural production has always depended on local Yellow River irrigation. To promote agricultural production, mulched planting technology, due to its heat preservation, water saving, and yield increases, has been widely promoted in HID. However, with the development of the economy, the use of industrial water and domestic water in HID is increasing. Meanwhile, because of policy regulation, the amount of water diverted from the Yellow River will decrease by 20% (from 5 billion m³ to 4 billion m³) in the next 10 years [1]. The problem of insufficient agricultural water use is becoming increasingly serious. Therefore, it is imperative to develop methods for efficient water-saving irrigation. Simultaneously, alternative water sources for irrigation should be found for the sustainable development of agriculture in HID.

Given the combination of the long-term excessive irrigation use of the Yellow River and the effects of low precipitation and high evaporation, brackish water (salinity concentration ranging from 2 to 5 g·L⁻¹) reserves in HID are abundant (up to 8.86 billion m³) and have potential for use [2]. However, irrigation with brackish water may lead to the accumulation of salt in the soil tillage layer, resulting in varying degrees of soil salinization and alkalization. These soil conditions cause a decline in the fertility and growth of crops as a result of salinity stress [3,4]. Spring maize, with a growing stage from April to September, is the second largest grain crop in HID (planting area accounts for about 30% of total planting area in HID [5]), after sunflower. Maize growth is sensitive to salt in soil: when the EC_{1.5} of the soil tillage layer exceeds 114 uS·cm⁻¹, its yield begins to decline; and when the EC_{1.5} of the soil tillage layer exceeds 1473 uS·cm⁻¹, maize stops growing [5]. Unreasonable irrigation method with brackish water may lead to a significant decrease in maize yield. In response to this, drip irrigation, which is characterized by delivering a small volume of irrigation water at a high frequency, was reported to be an important method that can effectively use brackish water resources [6]. When using brackish water for drip irrigation, salt only accumulates at the edge of the wetting zone, in which the salt content is relatively low and conducive to crop growth [7]. Therefore, exploring the effective use of brackish water with drip irrigation to guarantee maize yield and improve soil safety should be among HID's priorities.

Irrigation water salinity not only accelerates the process of soil salinization and alkalization but also affects the available soil nitrogen, enzymes, microorganisms, nitrification, and denitrification, all of which can affect soil N₂O emission [8,9]. As an important greenhouse gas, N₂O is a major contributor to the destruction of the ozone layer through its involvement in photochemical reactions [10]. Its global warming potential is more than 260 times greater than that of CO₂ [11]. Most N₂O emissions from agricultural soils are products of nitrification and denitrification, accounting for about 59.4% of the global anthropogenic emissions of N₂O [12,13]. Therefore, reducing soil N₂O emissions from farmland ecosystems is an urgent task. Previous studies on the factors influencing soil N₂O emissions from farmland have mostly focused on the amount of fertilizer, fertilizer type, irrigation method, soil amendment, and C/N ratio [14–17]. However, research is lacking and conflicting on the effect of saline irrigation water on N₂O emission. Judging from the existing research, salinity has been found to both significantly stimulate [12,18–20] and inhibit soil N₂O emissions [21–23], or produced no significant effect [24–26]. For example, Maucieri et al. indicated that irrigation water salinity remarkably promoted N₂O emission in their incubation experiment in Australia [20]. Kontopoulou et al. reported that irrigation water salinity did not affect the emissions of N₂O in Greek soybean fields [24]. Zou et al. found that irrigation water salinity significantly inhibited soil N₂O emissions in a winter wheat and summer maize fields in Beijing, China [21]. However, these research efforts have mostly focused on short-term soil incubation experiments or one-year field experiments, and most did not consider changes in soil conditions caused by brackish water irrigation and climate change, and relevant research has not been conducted in HID. Studies using bare soil, an important part of the mulching system in farmland, have not been reported until now. Exploring N₂O emissions from soil at different locations that use film mulching can reflect the actual emission process. Therefore, further studies should be conducted.

To address the above issues, we assumed that irrigation water salinity would affect the soil properties, N₂O emissions, yield, and irrigation water use efficiency (IWUE). Therefore, our objectives in the present study were to: (1) Investigate the response of soil properties and N₂O emissions to different levels of irrigation water salinity, (2) evaluate the effects of irrigation water salinity on the maize yield and IWUE, and (3) propose an efficient brackish water irrigation method that will allow HID to lessen the risk of soil salinization and alkalization, N₂O emission, and yield reduction.

2. Materials and Methods

2.1. Experimental Site

We used the Shuguang Experimental Station (40°46' N, 107°24' E, and elevation of 1039 m) to conduct field experiments with spring maize for two seasons (2017 and 2018). The location of the experimental site is illustrated in Figure 1. The region has a typically arid continental climate with an average annual precipitation of 105 mm, average annual evaporation of 2306.5 mm, average annual temperature of 7.8 °C, and average annual relative humidity of 48.9% [2,27]. The soil properties are shown in Table 1. The daily meteorological data of the spring maize growth stage in both seasons were recorded by the standard farmland meteorological station (FY-1000, Fortune Flyco, Wuhan, China) in the experimental station (Figure 2). During the growth stage in 2017 and 2018, the precipitation was 53.5 and 202 mm, the average daily (day and night) air temperature was 22.0 and 21.4 °C, and the average soil temperature (during the sample time) was 22.0 °C and 23.1 °C, respectively.

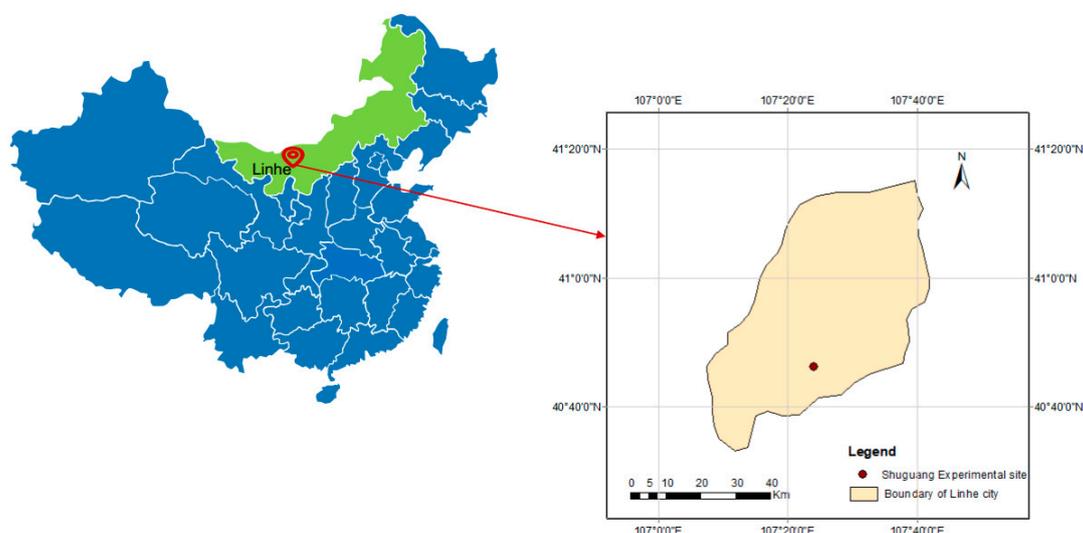


Figure 1. Location of the experimental station.

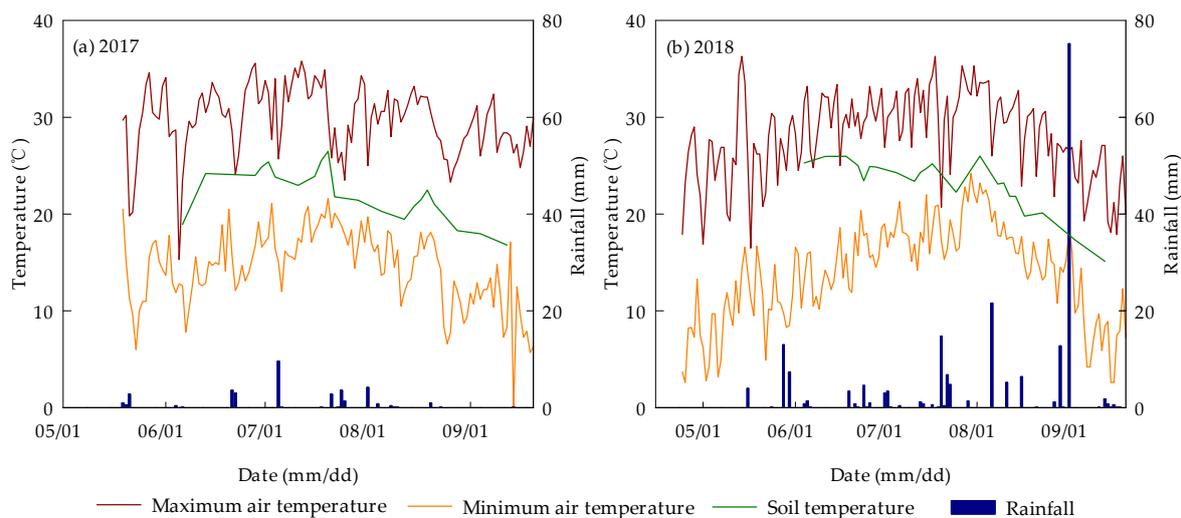


Figure 2. Field meteorological data during the spring maize growth stage in (a) 2017 and (b) 2018.

Table 1. Initial properties of the soil tillage layer in the experimental fields in 2017.

Soil Type	Soil Texture			Soil Bulk	Field	Saturated Hydraulic Conductivity	Ec _{1:5}	pH	Soil NO ₃ ⁻
	Clay (%)	Silt (%)	Sand (%)	Density (g·cm ⁻³)	Capacity (g·g ⁻¹)	(10 ⁻⁵ ·cm·s ⁻¹)	(uS·cm ⁻¹)		-N (mg·kg ⁻¹)
Silty loam	7.694	62.379	29.927	1.5	0.198	5.11	393	8.21	33.38

2.2. Experimental Design and Field Management

There were four treatments in this field experiment: (1) groundwater drip irrigation with salinity of 1.1 g·L⁻¹ (T1), (2) brackish water drip irrigation with salinity of 2.0 g·L⁻¹ (T2), (3) brackish water drip irrigation with salinity of 3.5 g·L⁻¹ (T3), and (4) brackish water drip irrigation with salinity of 5.0 g·L⁻¹ (T4). The four treatments were laid out in randomized complete blocks with three replicates for a total of 12 plots. There were 1-m buffer channels between adjacent plots to avoid interaction between the treatments.

Seeds of the spring maize hybrid Ximeng No.3358, selected as the experimental crop, were sown on 26 April 2017 and 28 April 2018, and harvested on 12 September 2017 and 15 September 2018. The growth stages lasted 140 and 141 days, respectively. The layout of the experimental plot is shown in Figure 3. Two rows of spring maize were planted in each bed. The intra-row spacing was 0.3 m and the inter-row spacing was 0.8 m. The surface of the intra-row soil was covered with plastic mulch. The planting density of the maize was 60,000 plants·ha⁻¹. Drip irrigation belts were arranged in the intra-row center. The thickness of the drip irrigation belts applied in the experiment was 0.4 mm, and the lateral diameter of the drip irrigation belts was 16 mm. The drippers were classified as embedded type. The interval between the drippers was 0.3 m, and the average discharge of each dripper was 2.0 L·h⁻¹. To satisfy the demand for different levels of irrigation water salinity, we used the groundwater of the experimental station and added an equal ratio of NaCl/KCl (Table 2). On the basis of previous publications, the same amounts of irrigation (300 mm) and nitrogen (300 kg·ha⁻¹) were applied for each treatment in the two seasons of the experiment [28,29]. The drip irrigation frequency was designed to be 6 days, and the irrigation amount was 15–25 mm each time [30]. Before they were sown, all plots were fertilized with 375 kg·ha⁻¹ diammonium phosphate and 75 kg·ha⁻¹ urea, and the fertilizers were applied to the soil tillage layer (0–20 cm) by machine [28,29]. The residual nitrogen was used for fertilization in the jointing stage, heading stage, and filling stage at a ratio of 2:2:1 in drip irrigation treatments [31]. The amounts of water and fertilizer were measured using a water meter (DN25, Aimeihui, Zhejiang, China) and a proportional fertilizer pump (Mixrite 2504, Tefen, Kibbutz Nahsholim, Israel) in each plot. The irrigation and fertilization dates for each treatment in 2017 and 2018 are shown in Figure 4.

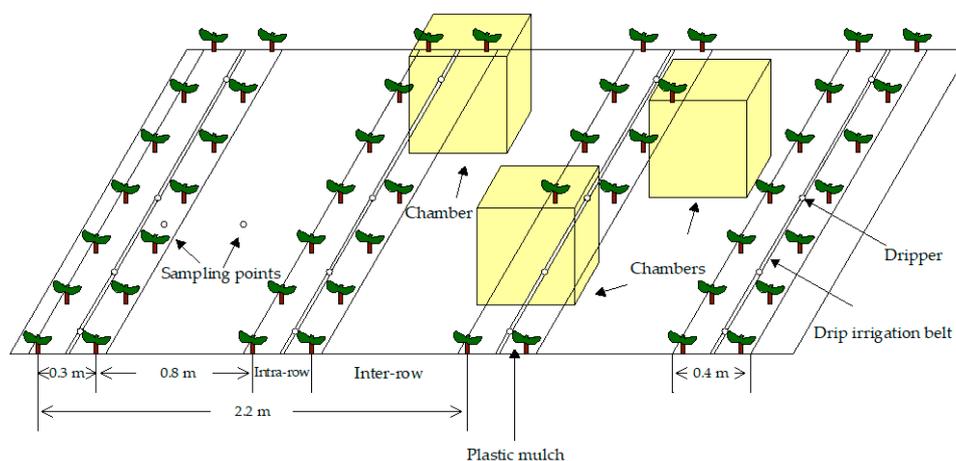
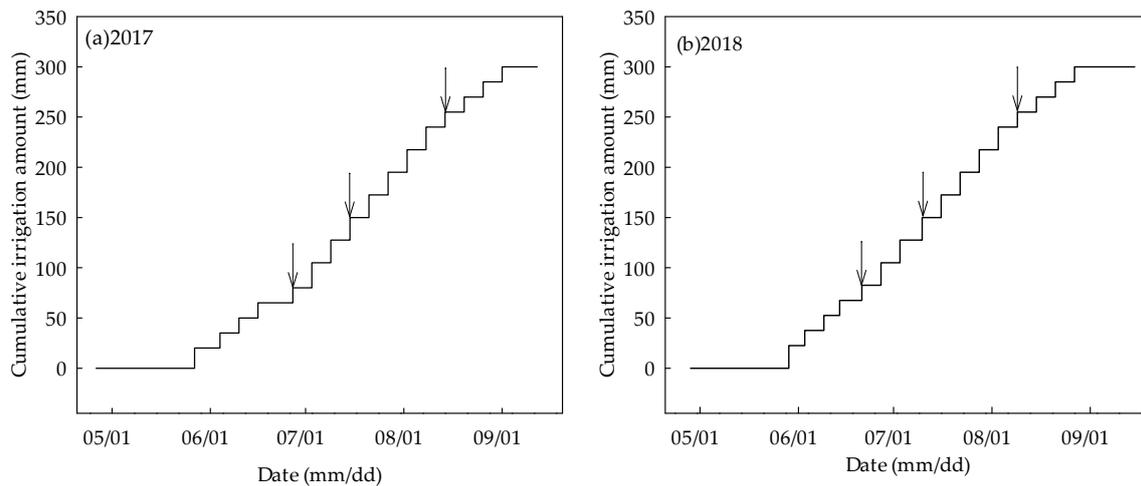
**Figure 3.** Layout of experimental plot.

Table 2. Iron contents of irrigation water used in the experiment.

Salinity (mg·L ⁻¹)	Iron Contents (mg·L ⁻¹)							
	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	CO ₃ ²⁻	SO ₄ ²⁻	HCO ₃ ⁻
1157	90.2	48.6	152.6	41.2	141.8	0	240.2	442.4
2000	90.2	48.6	355.0	212.8	610.8	0	240.2	442.4
3500	90.2	48.6	715.2	518.4	1445	0	240.2	442.4
5000	90.2	48.6	1075.8	823.8	2279	0	240.2	442.4

**Figure 4.** Detailed irrigation and fertilization dates for each treatment in (a) 2017 and (b) 2018. Note: Solid arrows represent fertilization events in drip irrigation treatments.

2.3. Measurement Method

2.3.1. Soil N₂O Emission

Soil N₂O gas samples were collected with a static chamber and analyzed by gas chromatography [32]. The sampling chamber was divided into a top chamber (50 × 50 × 50 cm) and a ground chamber (50 × 50 × 15 cm). The stainless-steel top chamber was covered with a foam board to prevent the temperature from rising too quickly, and two battery-operated fans were equipped to mix the gas. A thermometer slot was employed in the top chamber to measure the temperature during sampling. One week before sampling, the ground chamber was inserted in the center of each plot at a soil depth of 15 cm until the spring maize harvest. To represent the actual N₂O emission flux during drip irrigation with film mulching, the ground chamber was buried according to the intra- and inter-row proportions. In 2018, the ground chambers were also embedded in and between the rows of each plot to explore the relationship between N₂O emissions and different locations. During sampling, the convex part of the top chamber was placed into the groove of the bottom chamber and water-sealed with no air exchange. A 100-mL gas sample was extracted from the chamber using a syringe 0, 10, 20, and 30 min after closing the chamber, and the samples were then transferred to sampling bags and tested within a week. The soil N₂O samples were collected from 08:30 to 11:30 a.m. every 7–14 days, and there were additional samplings on the first, third, fifth, and seventh days after fertilization [33,34]. The concentration of N₂O was measured by gas chromatography (Agilent 7890A, Agilent Technologies, Santa Clara, CA, USA), and its emission flux (F , $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was determined by the following equation [35]:

$$F = \rho \times H \times \left(\frac{\Delta c}{\Delta t}\right) \times \left(\frac{273}{T}\right) \quad (1)$$

where ρ is the density of N_2O ($kg \cdot m^{-3}$) in standard temperature and pressure, H is the top chamber height (m), $\Delta c / \Delta t$ is the slope of N_2O concentration variation over time ($ppb \cdot h^{-1}$), and T is the average temperature during sampling (K).

The N_2O ($kg \cdot ha^{-1}$) cumulative flux (S) from spring maize soils was calculated by the following equation [36]:

$$S = \sum_i^n (F_i \times D_i) \quad (2)$$

where F_i represents the N_2O emission flux ($kg \cdot ha^{-1} \cdot day^{-1}$), D_i represents days between two sampling times (days), and n represents the sample number.

2.3.2. Soil Properties

When sampling the gas, soil samples were acquired from a depth of 0–0.3 m, and sampling points were located between intra-row maize plants and from the center of inter-row spaces in each plot. Part of the soil was packed in an aluminum box and dried at 105 °C for 8–10 h. The remaining soil samples were air-dried, pulverized, and then sifted through a 1 mm sieve. A 10 g subsample was weighed and added to 50 mL of deionized water. After the mixture was shaken, left to stand, and centrifuged, the supernatant $EC_{1:5}$ ($\mu S \cdot cm^{-1}$) and pH were measured by a multi-parameter tester (SG23, Mettler Toledo, Shanghai, China). Another 5 g subsample was weighed and added to 50 mL of a KCl solution. After the mixture was shaken, left to stand, and filtered, the NO_3^- content ($mg \cdot kg^{-1}$) in the supernatant was measured by a continuous flowing analyzer (Alliance FUTURA, AMS, Frépillon, France). After the spring maize harvest in 2018, the saturated hydraulic conductivity ($cm \cdot s^{-1}$) of 0–20 cm of soil in the intra-row was measured by the constant-head method.

2.3.3. Spring Maize Yield and IWUE

At harvest time, 6 maize plants from each plot were chosen to measure yield. Maize kernel samples were weighed after sun drying and threshing, and the actual yield was converted according to the number of plants. The IWUE was calculated by the following equation:

$$E = \frac{Y}{Q} \quad (3)$$

where E represents the IWUE ($kg \cdot m^{-3}$), Y represents the yield of spring maize ($kg \cdot ha^{-1}$), and Q represents the cumulative amount of irrigation water ($m^3 \cdot ha^{-1}$).

2.3.4. Statistical Analysis

The ANOVA procedure in SPSS software (IBM, Armonk, NY, USA) was used to statistically analyze the data. A Duncan multiple comparisons test was used to make multiple comparisons of annual average values. Pearson's correlation analysis procedure in SPSS software (IBM, Armonk, NY, USA) was used to compare the correlations between soil N_2O emission, soil properties, and maize yield. The confidence level is 95%.

3. Results

3.1. Soil Water Content

Figure 5 shows the average intra- and inter-row soil water content of spring maize under different treatments in 2017 and 2018. The soil water content in intra-row soil was higher than that of inter-row soil under T1–T4 treatments ($p < 0.05$). On the whole, the soil water content in 2018 was higher than in 2017 ($p < 0.05$), which might be attributed to the large volumes and high frequency of precipitation in 2018 (Figure 2). The irrigation water salinity had a significant effect on the soil water content ($p < 0.05$). The intra- and inter-row soil water content under T4 treatment was much higher than that under

T1–T3 treatments ($p < 0.05$), with intra-row increases of 25.55–35.43% and 19.66–29.09% and inter-row increases of 41.38–57.69% and 23.19–37.10% in 2017 and 2018, respectively.

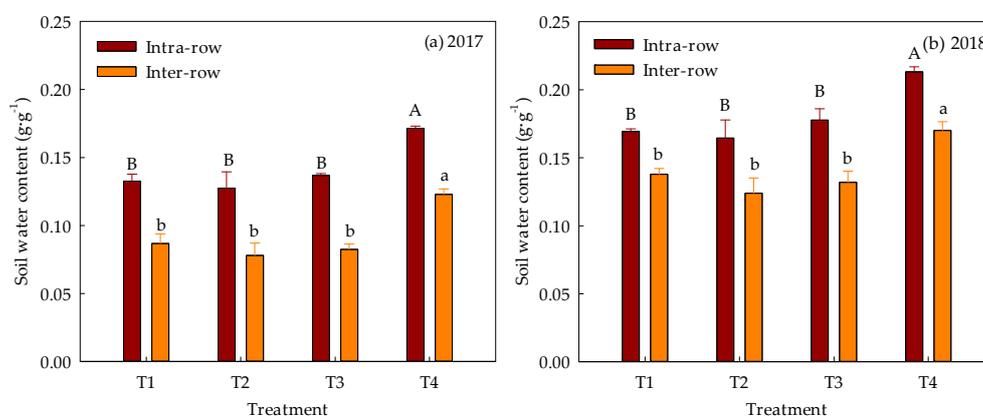


Figure 5. Average soil water content during the growth stage for spring maize under different treatments in (a) 2017 and (b) 2018. Note: The data are the average values of 15 measurements during the growth stage; the error line in the figure represents the stand deviation ($n = 3$); different capital letters between treatments represent that the difference in intra-row is significant at the 0.05 level; different lowercase letters between treatments represent that the difference in inter-row is significant at the 0.05 level.

3.2. Soil Salinity

Figure 6 shows the average $EC_{1.5}$ in intra- and inter-row soil of spring maize under different treatments in 2017 and 2018. The $EC_{1.5}$ in 2018 was lower than that in 2017 in both intra- and inter-row soil ($p < 0.05$), which might be caused by the fact that the heavy precipitation has a leaching effect on the soil salt in 2018. The irrigation water salinity had a significant effect on the soil $EC_{1.5}$ ($p < 0.05$). The intra-row soil $EC_{1.5}$ under T3–T4 treatments was much higher than that under T1–T2 treatments ($p < 0.05$), with the former being higher than the latter by 43.59–85.33% in 2017 and 31.37–65.35% in 2018, and there was a significant difference in the soil $EC_{1.5}$ between T3 and T4 treatments ($p < 0.05$). The inter-row soil $EC_{1.5}$ under T4 treatment significantly increased by 62.92–77.60% in 2017 and 44.90–95.41% in 2018 compared with that under T1–T3 treatments ($p < 0.05$), and the difference between T3 treatment and T1–T2 treatments in 2018 was significant ($p < 0.05$).

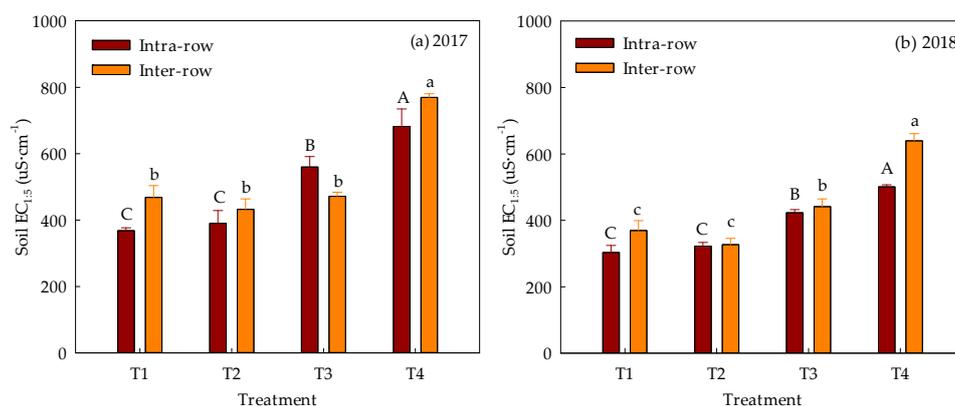


Figure 6. Average soil $EC_{1.5}$ during the growth stage of spring maize under different treatments in (a) 2017 and (b) 2018. Note: The data are the average values of 15 measurements during the growth stage; the error line in the figure represents the stand deviation ($n = 3$); different capital letters between treatments represent that the difference in intra-row is significant at the 0.05 level; different lowercase letters between treatments represent that the difference in inter-row is significant at the 0.05 level.

3.3. Soil pH Value

Figure 7 shows the average pH value in the intra- and inter-row soil of spring maize under different treatments in 2017 and 2018. The pH value of soil tillage layer under all treatments in 2018 increased to varying degrees compared with that in 2017, and the range increased with the increase in irrigation water salinity ($p < 0.05$). Irrigation water salinity had a significant effect on pH value in the soil tillage layer ($p < 0.05$). In 2017, the pH value under T3–T4 treatments increased by 0.48–1.68% compared with that under T1–T2 treatments in intra-row soil ($p < 0.05$), and the difference between T3 and T4 treatments was significant in intra-row soil ($p < 0.05$), but there was no significant difference in pH between T1–T4 treatments in inter-row soil ($p > 0.05$). In 2018, the pH value under T3–T4 treatments increased by 2.13–4.06% compared with that under T1–T2 treatments in intra-row soil ($p < 0.05$), and the difference between T3 and T4 treatments was significant ($p < 0.05$). There were significant differences in pH values among T1–T4 treatments in inter-row soil ($p < 0.05$).

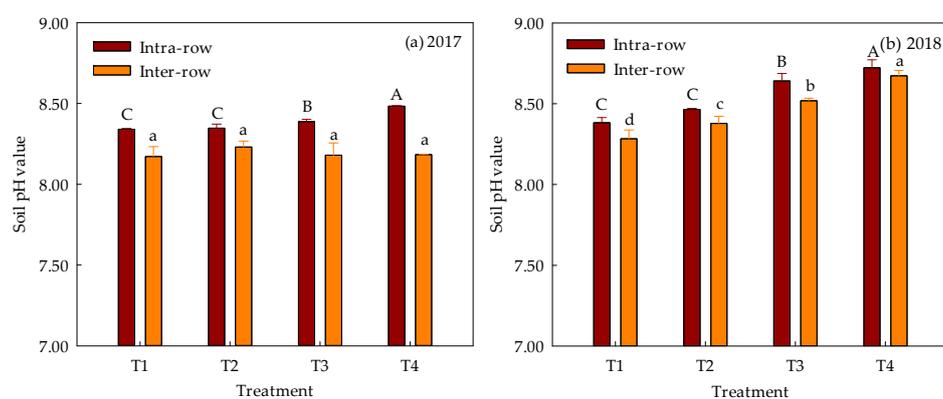


Figure 7. Average soil pH value for the growth stage of spring maize under different treatments in (a) 2017 and (b) 2018. Note: The data are the average values of 15 measurements during the growth stage; the error line in the figure represents the stand deviation ($n = 3$); different capital letters between treatments represent that the difference in intra-row is significant at the 0.05 level; different lowercase letters between treatments represent that the difference in inter-row is significant at the 0.05 level.

3.4. Soil NO_3^- Content

Figure 8 shows the average intra- and inter-row soil NO_3^- content of spring maize under different treatments in 2017 and 2018. On the whole, the soil NO_3^- content in inter-row soil was higher than that of intra-row soil ($p < 0.05$). Due to the leaching effect on soil NO_3^- content by heavy precipitation in 2018 (Figure 2), NO_3^- content in both intra- and inter-row soil was lower than that in 2017 ($p < 0.05$). Irrigation water salinity had no significant effect on the average NO_3^- content in intra- and inter-row soil ($p > 0.05$).

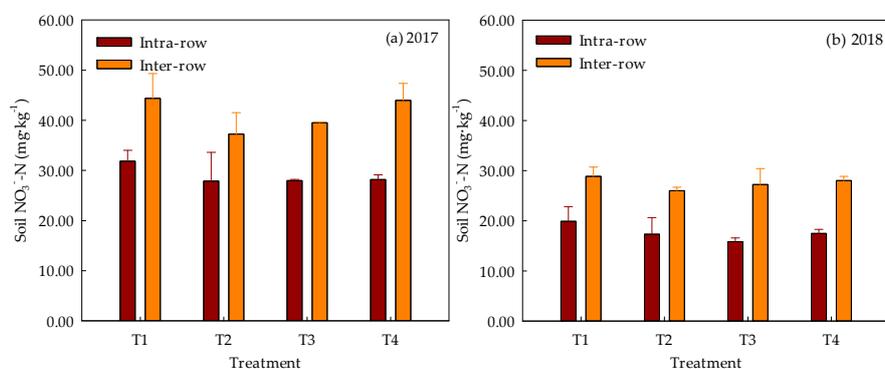


Figure 8. Average soil NO_3^- content at the growth stage of spring maize under different treatments in (a) 2017 and (b) 2018. Note: The data are the average values of 15 measurements during the growth stage; the error line in the figure represents the stand deviation ($n = 3$).

3.5. Saturated Soil Hydraulic Conductivity

The results of saturated soil hydraulic conductivity (K_{sat}) at harvest in 2018 are shown in Figure 9. Under all treatments, K_{sat} decreased to varying degrees compared with that before sowing (Table 1); this decrease was due to the tillage of the surface soil before sowing. Irrigation water salinity significantly affected K_{sat} ($p < 0.05$). K_{sat} decreased with the increase in irrigation water salinity: the value was 54.92–75.93% lower for the T2–T4 treatments than that for the T1 treatment.

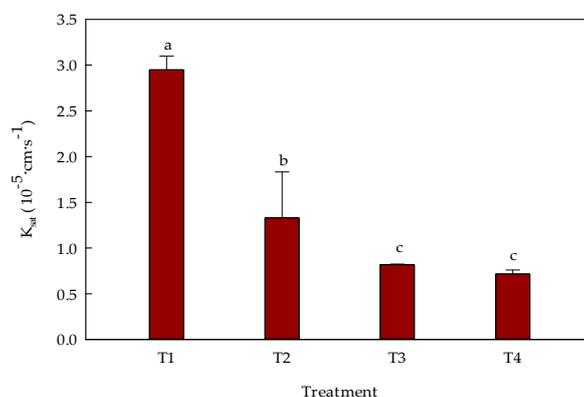


Figure 9. Effect of irrigation water salinity on saturated soil water conductivity. Note: The error line in the figure indicates the standard deviation ($n = 3$); different letters between treatments represent a significant difference at the 0.05 level.

3.6. Soil N_2O Emission Flux

3.6.1. Seasonal N_2O Emission Flux

The soil N_2O emission flux in 2017 and 2018 had a similar pattern during the growth stage of spring maize (Figure 10). The soil was proven to be the emission source of N_2O . We observed six peaks of N_2O emission flux in total, and they appeared one to five days after fertilization in 2017 and 2018. Compared with the peak value in the one to five days after fertilization, the average peak values of N_2O emissions in treatments T1, T2, T3, and T4 were 81.57, 89.30, 95.14, and 139.32 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ in 2017, and there was a significant difference between the T4 treatment and T1–T3 treatments ($p < 0.05$). The average peak values of N_2O emissions in treatments T1, T2, T3, and T4 were 100.62, 114.30, 154.45, and 184.23 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ in 2018, and there was a significant difference between T3–T4 treatments and the T1 treatment ($p < 0.05$). Overall, the N_2O peak emission flux increased with the increase in irrigation water salinity. There was no peak N_2O emission with irrigation only.

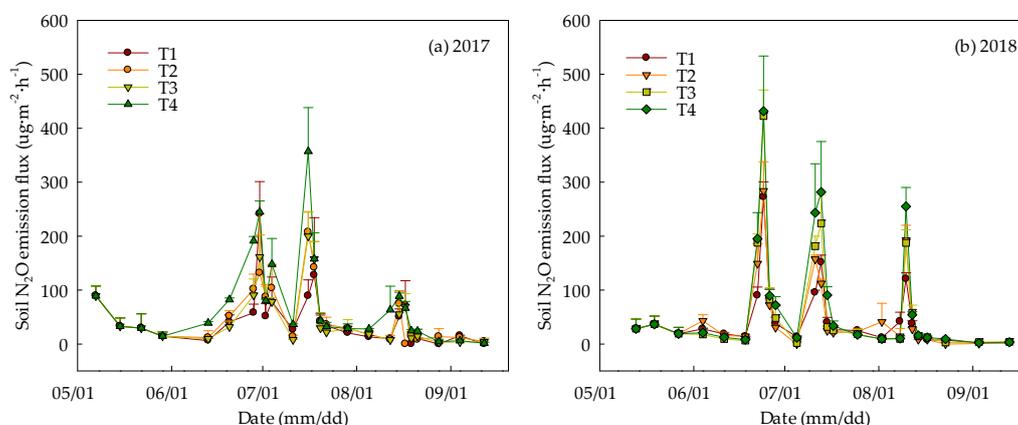


Figure 10. Changes in N_2O emission flux from soil during the growth stage of spring maize under different treatments in (a) 2017 and (b) 2018. Note: The error line in the figure indicates the standard deviation ($n = 3$).

3.6.2. Seasonal N₂O Emission Flux from Different Locations

Figure 11 show that the N₂O emission flux from intra- and inter-row soil reached peaks from the first to fifth day after fertilization. The average peak values of N₂O emissions in treatments T1, T2, T3, and T4 were 178.09, 207.13, 224.77, and 305.32 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ in intra-row soil, and there was a significant difference between the T4 treatment and T1–T3 treatments ($p < 0.05$). The average peak values of N₂O emissions in treatments T1, T2, T3, and T4 were 57.04, 62.08, 114.89, and 116.11 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ in inter-row soil, and there was a significant difference between T3–T4 treatments and T1–T2 treatments ($p < 0.05$). Meanwhile, the peak N₂O emission flux from intra-row soil was higher than that of inter-row soil under T1–T4 treatments ($p < 0.05$).

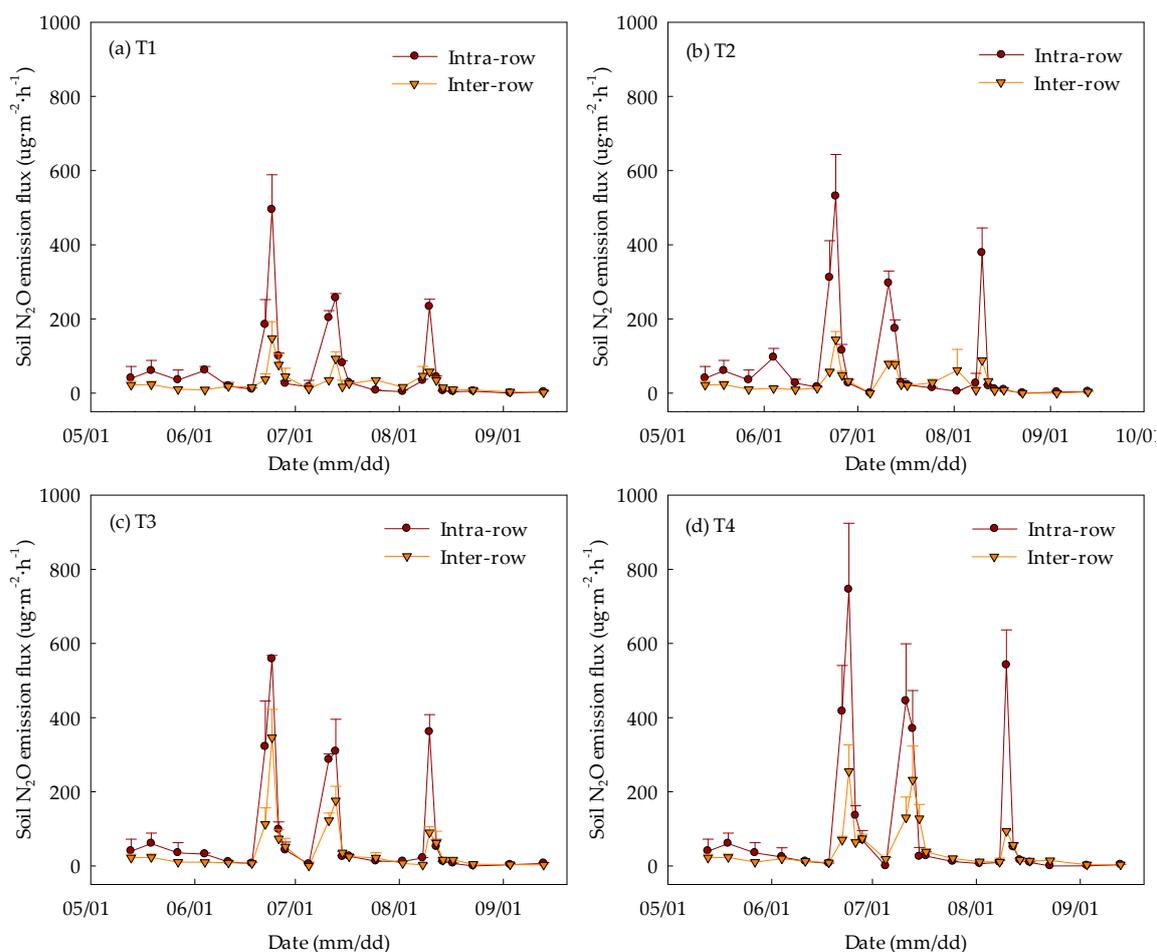


Figure 11. Changes in N₂O emission flux at different soil locations during the growth stage of spring maize under different treatments in 2018: (a) T1; (b) T2; (c) T3; (d) T4. Note: The error line in the figure indicates the standard deviation ($n = 3$).

3.6.3. N₂O Cumulative Flux

The cumulative N₂O flux under all treatments in 2017 and 2018 is shown in Figure 12a. The cumulative N₂O flux under T4 treatment increased by 51.18–82.86% in 2017 and 19.83–44.79% in 2018 compared with that under T1–T3 treatments, and the difference between T4 treatment and T1–T2 treatments in the two years was significant ($p < 0.05$).

The cumulative N₂O flux at different locations under all treatments in 2018 is shown in Figure 12b. The cumulative N₂O flux under T4 treatment increased by 22.49–44.76% in intra-row soil and 14.77–46.38% in inter-row soil compared with that under T1–T3 treatments, and the difference between T4 treatment and T1 treatment in intra- and inter-row soil was significant ($p < 0.05$). Also, the cumulative

N_2O emission from intra-row soil was significantly higher than that of inter-row soil under T1–T4 treatments ($p < 0.05$).

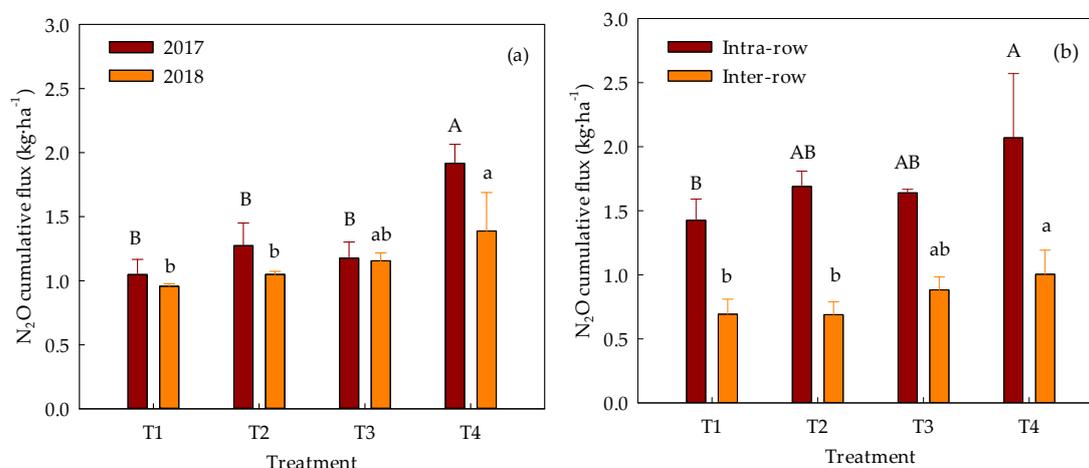


Figure 12. Cumulative N_2O flux from soil during the growth stage of spring maize under different treatments: (a) cumulative N_2O flux in 2017 and 2018; (b) cumulative N_2O flux in intra- and inter-row. Note: The error line in the figure indicates the standard deviation ($n = 3$); different capital letters between treatments represent that the difference in 2017 or intra-row is significant at the 0.05 level; different lowercase letters between treatments represent that the difference in 2018 or inter-row is significant at the 0.05 level.

3.7. Spring Maize Yield and IWUE

The spring maize yield and IWUE under all treatments in 2017 and 2018 is shown in Figure 13. The increase in irrigation water salinity significantly reduced spring maize yield and IWUE ($p < 0.05$). After irrigation with brackish water for one year, the yields under T3–T4 treatments significantly decreased by 11.81–23.93% compared with that under T1 treatment ($p < 0.05$). After two years, the yields under T2–T4 treatments significantly decreased by 13.86–31.47% compared with that under T1 treatment ($p < 0.05$). The average IWUE under T1 treatment was significantly larger than that under T3–T4 treatments after irrigation with brackish water in 2017 and 2018 ($p < 0.05$).

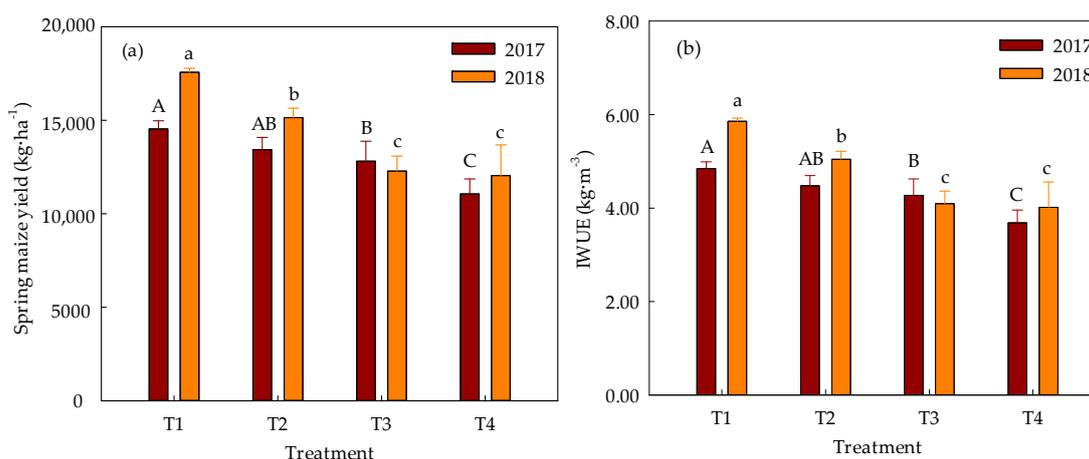


Figure 13. The yield and IWUE of spring maize under different treatments in 2017 and 2018: (a) spring maize yield; (b) IWUE. Note: The error line in the figure indicates the standard deviation ($n = 3$); different capital letters between treatments represent that the difference in 2017 is significant at the 0.05 level; different lowercase letters between treatments represent that the difference in 2018 is significant at the 0.05 level.

3.8. Correlation Analysis among Irrigation Water Salinity, Soil Properties, N₂O Emissions and Maize Yield

The correlation between soil N₂O emission flux and soil properties is shown in Figure 14. There was a significant linear correlation between soil N₂O emission flux and soil temperature when the soil temperature ranged from 13.7 °C to 30.1 °C, indicating that the soil temperature was an important factor causing differences in seasonal N₂O emission flux. The soil water content and soil N₂O emission fluxes were significantly correlated in 2017 but not in 2018, which is attributed to the heavy precipitation in 2018. N₂O emission was significantly correlated with the soil water content in intra-row soil, but not with inter-row soil, indicating that the intra-row soil water content was an important factor driving differences in seasonal N₂O emissions. In 2017 and 2018, soil N₂O emissions were significantly correlated with soil NO₃⁻. The concentration of soil NO₃⁻ was 33.07–51.76 mg·kg⁻¹ and 25.50–39.78 mg·kg⁻¹ when N₂O reached its emission peak in 2017 and 2018. Soil N₂O emission flux was significantly correlated with soil NO₃⁻ in intra-row soil but not in inter-row soil, indicating that the NO₃⁻ in intra-row soil was the main factor causing differences in seasonal N₂O emission.

The correlation among irrigation water salinity, soil properties, soil N₂O emission flux and maize yield is shown in Tables 3 and 4. The result indicated that high-salinity brackish water irrigation significantly increased the water content of the soil tillage layer by affecting the crop's absorption of water. High-salinity brackish water also increased the salinity content and pH value, and decreased the saturated hydraulic conductivity of the soil tillage layer, thus accelerating the soil salinization and alkalization process. The combined effect of the above results lead to a decrease in the yield of spring maize.

Table 3. Relationship among irrigation water salinity, soil properties, N₂O emission flux, and yield of spring maize in 2017.

Variables	IWS	SWC	EC _{1:5}	pH	NO ₃ ⁻ -N	N ₂ O	Yield
IWS	1						
SWC	0.788 **	1					
EC _{1:5}	0.934 **	0.933 **	1				
pH	0.706 *	0.638 *	0.720 **	1			
NO ₃ ⁻ -N	-0.097	0.315	0.185	-0.088	1		
N ₂ O	0.753 **	0.756 **	0.802 **	0.672 *	-0.030	1	
Yield	-0.877 **	-0.677 *	-0.811 **	-0.571	0.219	-0.767 **	1

Note: IWS is irrigation water salinity, SWC is soil water content; ** and * represents a significant correlation at the 0.01 and 0.05 levels, respectively.

Table 4. Relationship among irrigation water salinity, soil properties, N₂O emission flux, and yield of spring maize in 2018.

Variables	K _{sat}	IWS	SWC	EC _{1:5}	pH	NO ₃ ⁻ -N	N ₂ O	Yield
K _{sat}	1							
IWS	-0.826 **	1						
SWC	-0.347	0.783 **	1					
EC _{1:5}	-0.630 *	0.948 **	0.905 **	1				
pH	-0.833 **	0.991 **	0.743 **	0.925 **	1			
NO ₃ ⁻ -N	0.625 *	-0.259	0.142	-0.040	-0.269	1		
N ₂ O	-0.619 *	0.837 **	0.674 *	0.799 **	0.803 **	-0.133	1	
Yield	0.875 **	-0.885 **	-0.530	-0.751 **	-0.898 **	0.367	-0.630 *	1

Note: IWS is irrigation water salinity, SWC is soil water content, K_{sat} is saturated soil hydraulic conductivity; ** and * represents a significant correlation at the 0.01 and 0.05 levels, respectively.

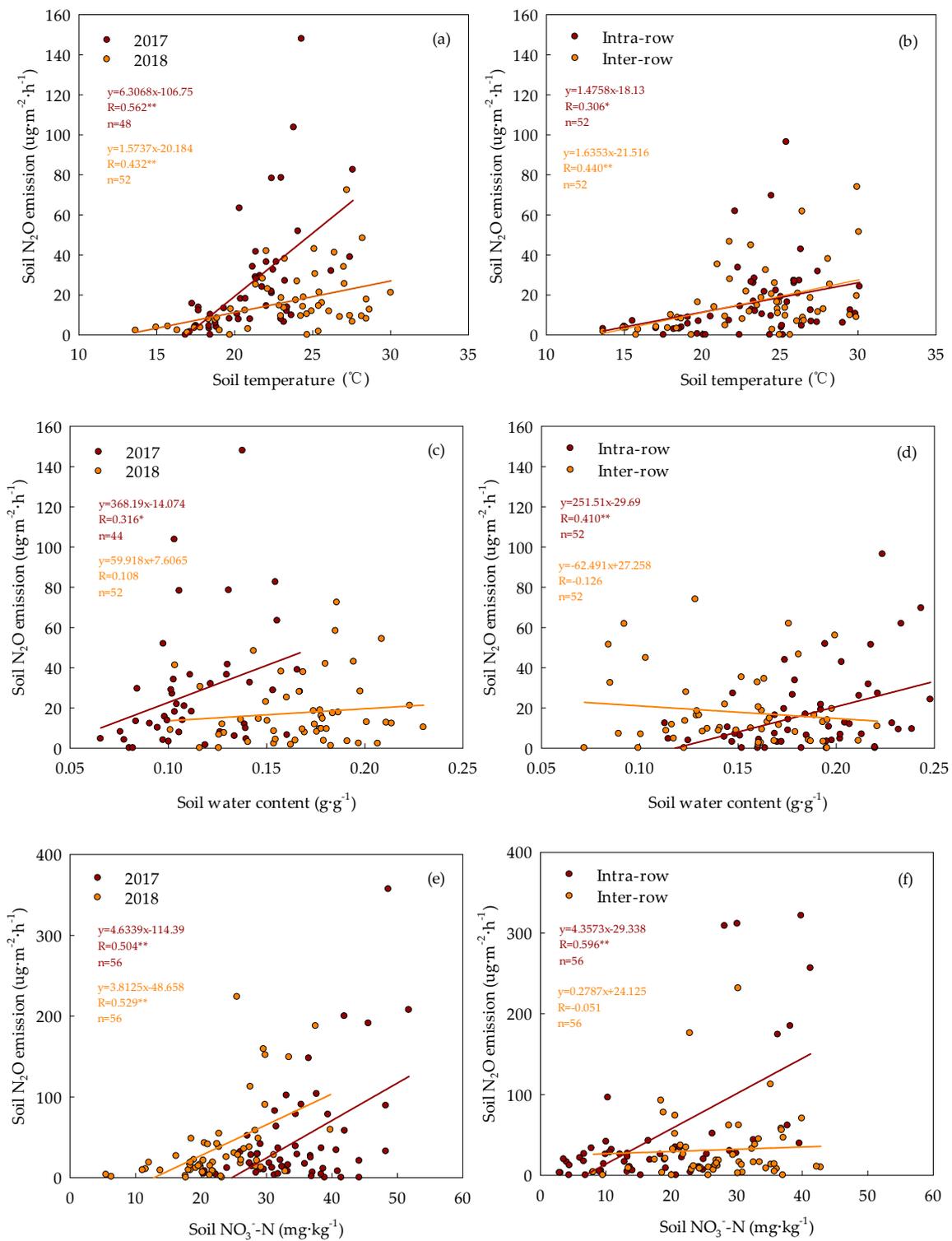


Figure 14. Relationship between (a) soil N₂O emission and soil temperature in different years, (b) soil N₂O emission and soil temperature in different locations, (c) soil N₂O emission and soil water content in different years, (d) soil N₂O emission and soil water content in different locations, (e) soil N₂O emission and soil NO₃⁻ in different years, and (f) soil N₂O emission and soil NO₃⁻ in different locations. Note: ** and * represents a significant correlation at the 0.01 and 0.05 levels, respectively.

4. Discussion

4.1. Soil Properties

Our results are consistent with previous studies, which indicate that irrigation with brackish water had adverse effects on soil properties (Tables 3 and 4) [20,37,38]. These results are attributed to irrigation with high-salinity brackish water changing the soil osmotic potential, making it difficult for plants to absorb water and slowing transpiration [3]. High-salinity brackish water is rich in Na^+ (Table 2). The sodium adsorption ratio of irrigation water increased, leading to an increase in soil pH (Figure 7), a decrease in soil hydraulic conductivity, and a decrease in the soil infiltration rate (Figure 9) [39,40]. As a result, soil compaction hindered the movement of water and salt in soil, resulting in an increase in the water and salinity content of the intra-row soil. There was a gradient of water potential between the intra- and inter-row soil under film mulching conditions (Figure 5). As a result of this gradient, salt migrated with water from intra-row soil to inter-row soil. This explains why brackish water irrigation increased the soil water content, salinity, and pH value in inter-row soil.

4.2. Soil N_2O Emission Dynamics

Nitrification and denitrification, in which soil microorganisms and enzymes participate, are the main pathways for N_2O emission in farmland soil [13]. Our result is consistent with the conclusion of Scheer et al. [41], who indicated that soil N_2O emissions increased significantly when fertilization and irrigation were simultaneously applied. In our study, the soil N_2O emission peaks occurred one to five days after simultaneous irrigation and fertilization; after peaking, N_2O emissions gradually returned to normal levels, i.e., the level before fertilization. This may be due to the significant linear correlation observed between N_2O emission flux and soil NO_3^- (Figure 14). Sufficient substrates were provided for soil nitrification and denitrification after topdressing urea, which promotes soil N_2O emission. Our results also show that the soil N_2O emission dynamics were significantly correlated with the soil water content and soil temperature (Figure 14). This finding is consistent with Chen et al.'s conclusion from their greenhouse tomato irrigation experiment, which indicated that the soil water content and soil temperature were the dominant factors driving the soil N_2O emission dynamics when fertilizer was not applied [42].

4.3. Effect of Irrigation Water Salinity on N_2O Emissions

Our study shows that irrigation water salinity had no effect on soil NO_3^- content (Figure 8), indicating that soil nitrification might not be affected by irrigation water salinity. We also found that the soil N_2O emission increased with the increase in irrigation water salinity. Although there was no correlation between the seasonal N_2O emission flux and seasonal soil $\text{EC}_{1:5}$, the average N_2O emission flux had a significant positive correlation with the average soil $\text{EC}_{1:5}$ (Tables 3 and 4), which is contrary to the correlation between N_2O emission and soil NO_3^- content. This indicates that the effect of salinity on N_2O emission was durative rather than explosive.

Although opposing results have been reported in some other papers, the discrepancy might be due to a threshold soil salinity level that directed the influence on nitrification and denitrification rates ($\text{EC}_{1:5} = 1130 \mu\text{S}\cdot\text{cm}^{-1}$) [43]. When the soil salinity was lower than the threshold, the increased nitrification and denitrification rates were attributed to the increase in soil salinity, whereas the nitrification and denitrification rates decreased when the soil salinity was higher than the threshold [43]. However, this value was higher than the soil $\text{EC}_{1:5}$ measurements in our experiment (Figure 6), indicating that salinity might increase the nitrification and denitrification rate. The increase in soil salinity might also result in reduced N_2O reductase activity, resulting in the promotion of N_2O accumulation in the denitrification process [44]. Because Na^+ , K^+ , and higher pH values have stronger salting-out potential, the solubility of N_2O in soil solution is expected to decrease after irrigation with high-salinity brackish water [45]. These processes could be a pathway by which salinity promotes N_2O emissions.

Because crop water uptake was restricted by irrigation water salinity, the water content in the soil tillage layer was significantly improved by using high-salinity brackish water irrigation compared with other treatments in the actual irrigation process (Figure 5). There was a positive correlation between soil N₂O emission flux and soil water content (Tables 3 and 4, and Figure 14). This agrees with the findings of previous studies [12,18,34,36,46], which reported that soil N₂O emission flux increased as the soil's saturated water content increased from 30% to 90%. This occurs because increased water content reduces the oxygen concentration and thereby induces soil nitrification and denitrification and thus the production of N₂O. This may be another pathway through which salinity promotes N₂O emission. In conclusion, 2.0 g·L⁻¹ brackish water irrigation has the potential to significantly reduce soil N₂O emission while saving freshwater resources.

Wang et al. observed the effect of alternating brackish water and freshwater irrigation on soil N₂O emission under the same experimental conditions as ours (Table 5) [26]. Their results indicated that irrigation water salinity and the alternating irrigation method had no significant effect on soil N₂O emission. Although this is contrary to our result, the reason may be that alternating irrigation reduces the effect of salinity on soil physical properties. Comparing this with our results, alternating brackish water and freshwater irrigation can potentially reduce soil N₂O emission.

Table 5. Effect of different brackish water irrigation methods on soil N₂O emission in 2017.

Current Research		Wang's Research [26]			
Treatment	N ₂ O Flux (ug·m ⁻² ·h ⁻¹)	Treatment	N ₂ O Flux (ug·m ⁻² ·h ⁻¹)	Treatment	N ₂ O Flux (ug·m ⁻² ·h ⁻¹)
2.0 g·L ⁻¹	52.30	2.0 g·L ⁻¹ 1:1	47.96	2.0 g·L ⁻¹ 1:2	44.86
3.5 g·L ⁻¹	51.10	3.5 g·L ⁻¹ 1:1	46.95	3.5 g·L ⁻¹ 1:2	41.73
5.0 g·L ⁻¹	78.17	5.0 g·L ⁻¹ 1:1	44.52	5.0 g·L ⁻¹ 1:2	40.66

Note: 1:1 means to irrigate with freshwater once after one instance of brackish water irrigation; 1:2 means to irrigate with freshwater once after two instances of brackish water irrigation.

4.4. Effect of Different Location on N₂O Emissions

The proportion of uncovered area in the farmland system cannot be neglected under film mulching conditions. Until now, research was lacking on N₂O emissions at different locations under film mulching conditions. Our results demonstrate a positive correlation between soil N₂O emission and soil NO₃⁻ content in intra-row soil, but there was no correlation with soil NO₃⁻ content in inter-row soil (Figure 14). After simultaneous irrigation and fertilization, the N₂O emission flux in intra- and inter-row soil of each treatment was improved to different extents, and this may have been caused by the horizontal diffusion of N₂O [47]. The average N₂O emission flux in intra- and inter-row soil increased as the irrigation water salinity increased, which might also be the result of the interaction between soil water and salinity (Tables 3 and 4). The result also indicates that soil N₂O emission in intra-row soil was larger than that in inter-row soil. This phenomenon may be ascribed to the fertilization position. In drip irrigation treatments, fertilizers and water can be applied to the root zone directly through drippers, causing intra-row soil to have better water and fertilizer conditions than inter-row soil.

4.5. Effect of Irrigation Water Salinity on Spring Maize Yield

Various studies have been conducted on the impact of irrigation water salinity on crop yield [37,38,48,49]. Zhu et al. and Feng et al. reported that the maize yield decreased with the increase in irrigation water salinity [37,49]. Our results show the same phenomenon. Compared with T1 treatment, the yield under T2–T4 treatments decreased by 7.60–23.93% and 13.86–31.47% in 2017 and 2018, respectively. This may be caused by the relatively poor resistance of maize to Na⁺ during the rapid growth stage [48]. The increasing irrigation water salinity caused an increase in Na⁺ in the soil, and irrigation with high-salinity water was found to likely lead to ion toxicity due to Na⁺ osmotic stress, resulting in a reduction in maize yield [50]. However, there was no significant difference between T1 and T2

treatments in 2017, indicating that it is feasible to use $2.0 \text{ g}\cdot\text{L}^{-1}$ brackish water for irrigation in the short term when freshwater resources are in short supply.

Wang et al. also observed the effect of alternating irrigation with brackish water and freshwater on spring maize yield under the same experimental conditions as ours (Table 6) [26]. Comparing their results with ours, we surmise that the yield of spring maize could improve by alternating irrigation using brackish water and freshwater compared with the yield when using brackish water irrigation alone. Alternating irrigation can reduce the accumulation of soil salinity and ion toxicity, thus increasing the yield. This means that alternating irrigation with brackish water and freshwater is another way to use brackish water resources in areas with scarce freshwater resources.

Table 6. Effect of different brackish water irrigation methods on spring maize yield in 2017.

Current Research		Wang's Research [26]			
Treatment	Yield ($\text{kg}\cdot\text{ha}^{-1}$)	Treatment	Yield ($\text{kg}\cdot\text{ha}^{-1}$)	Treatment	Yield ($\text{kg}\cdot\text{ha}^{-1}$)
$2.0 \text{ g}\cdot\text{L}^{-1}$	13,434	$2.0 \text{ g}\cdot\text{L}^{-1}$ 1:1	14,651	$2.0 \text{ g}\cdot\text{L}^{-1}$ 1:2	13,914
$3.5 \text{ g}\cdot\text{L}^{-1}$	12,822	$3.5 \text{ g}\cdot\text{L}^{-1}$ 1:1	13,208	$3.5 \text{ g}\cdot\text{L}^{-1}$ 1:2	13,636
$5.0 \text{ g}\cdot\text{L}^{-1}$	11,060	$5.0 \text{ g}\cdot\text{L}^{-1}$ 1:1	12,957	$5.0 \text{ g}\cdot\text{L}^{-1}$ 1:2	12,449

Note: 1:1 means to irrigate with freshwater once after one instance of brackish water irrigation; 1:2 means to irrigate with freshwater once after two instances of brackish water irrigation.

5. Conclusions

Irrigation with $3.5\text{--}5.0 \text{ g}\cdot\text{L}^{-1}$ brackish water promoted the accumulation of soil salt, increased the soil pH value, and reduced the soil water conductivity. By affecting the water absorption of crops, the soil water content increased after irrigation with $5.0 \text{ g}\cdot\text{L}^{-1}$ brackish water. Irrigation with high-salinity brackish water accelerated the degree of soil salinization and alkalization. On this basis, due to the interaction between soil water and soil salinity, soil N_2O emissions significantly increased by irrigation with $5.0 \text{ g}\cdot\text{L}^{-1}$ brackish water. Irrigation with $3.5\text{--}5.0 \text{ g}\cdot\text{L}^{-1}$ brackish water significantly reduced the yield of spring maize.

Compared with continuous irrigation with $3.5\text{--}5.0 \text{ g}\cdot\text{L}^{-1}$ brackish water, continuous irrigation with $2.0 \text{ g}\cdot\text{L}^{-1}$ brackish water or alternating irrigation with brackish water and freshwater could slow the degree of soil salinization and alkalization, reduce soil N_2O emissions, and increase maize yield. Thus, these are potential measures to solving the current agricultural water crisis in Hetao Irrigation District. These results can also provide references for areas considering the use of brackish water.

Author Contributions: F.L., P.Y., and C.W. designed the experiments; C.W., S.W., Y.W., and Z.X. conducted the experiments; S.R. contributed materials; C.W. analyzed the data and wrote the paper; P.Y., Y.Z., Y.X., and R.W. revised the paper.

Funding: This research was funded by the National Natural Science Foundation of China, grant numbers 51679239.

Acknowledgments: The authors thank Yiqiang Zhang, Yuhong Xia, and Xiangzhu Zhang for their valuable assistance with the experimental work.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Zhang, H.M.; Xiong, Y.W.; Huang, G.H.; Xu, X.; Huang, Q.Z. Effects of water stress on processing tomatoes yield, quality and water use efficiency with plastic mulched drip irrigation in sandy soil of the Hetao Irrigation District. *Agric. Water Manag.* **2017**, *179*, 205–214. [[CrossRef](#)]
- He, X.; Yang, P.L.; Ren, S.M.; Li, Y.K.; Jiang, G.Y.; Li, L.H. Quantitative response of oil sunflower yield to evapotranspiration and soil salinity with saline water irrigation. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 63–73. [[CrossRef](#)]
- Cucci, G.; Rubino, P.; Caliandro, A. Effects of irrigation water with different salt concentrations and SAR values on soil salinisation and sodification. *Ital. J. Agron.* **2003**, *7*, 41–48.

4. Wang, S.J.; Huang, G.H.; Yang, J.G.; Wang, J.; Tai, R.K.; Meng, L.G. Effect of irrigation with saline water on water-salt dynamic and spring wheat yield. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 27–33.
5. Tong, W.J.; Chen, Z.D.; Chen, F.; Liu, Q.; Li, Z.H.; Wen, X.Y.; Gao, H.Y.; Chen, A.P. Analysis of maize salt tolerance in Hetao irrigation district and its ecological adaptable region. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 131–137.
6. Wang, Q.J.; Shan, Y.Y. Review of research development on water and soil regulation with brackish water irrigation. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 117–126. [[CrossRef](#)]
7. Yaron, B.; Shalhevet, J.; Shimshi, D. Patterns of salt distribution under trickle Irrigation. In *Physical Aspects of Soil Water and Salts in Ecosystems*; Springer: Berlin, Germany, 1973; pp. 389–394.
8. Tam, N.F.Y. Effects of wastewater discharge on microbial populations and enzyme activities in mangrove soils. *Environ. Pollut.* **1998**, *102*, 233–242. [[CrossRef](#)]
9. Irshad, M.; Honna, T.; Yamamoto, S.; Eneji, A.E.; Yamasaki, N. Nitrogen mineralization under saline conditions. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 1681–1689. [[CrossRef](#)]
10. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st century. *Science* **2009**, *326*, 123–125. [[CrossRef](#)]
11. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P.; et al. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014.
12. Wei, Q.; Xu, J.Z.; Liao, L.X.; Li, Y.W.; Wang, H.Y.; Rahim, S.F. Water salinity should be reduced for irrigation to minimize its risk of increased soil N₂O emissions. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2114. [[CrossRef](#)]
13. Malla, G.; Bhatia, A.; Pathak, H.; Prasad, S.; Jain, N.; Singh, J. Mitigating nitrous oxide and methane emissions from soil in rice–wheat system of the Indo-Gangetic plain with nitrification and urease inhibitors. *Chemosphere* **2005**, *58*, 141–147. [[CrossRef](#)] [[PubMed](#)]
14. Ozlu, E.; Kumar, S. Response of surface GHG fluxes to long-term manure and inorganic fertilizer application in corn and soybean rotation. *Sci. Total Environ.* **2018**, *626*, 817–825. [[CrossRef](#)] [[PubMed](#)]
15. Mechler, M.A.A.; Jiang, R.W.; Silverthorn, T.K.; Oelbermann, M. Impact of biochar on soil characteristics and temporal greenhouse gas emissions: A field study from southern Canada. *Biomass Bioenerg* **2018**, *118*, 154–162. [[CrossRef](#)]
16. Maris, S.C.; Teira-Esmatges, M.R.; Català, M.M. Influence of irrigation frequency on greenhouse gases emission from a paddy soil. *Paddy Water Environ.* **2016**, *14*, 199–210. [[CrossRef](#)]
17. Pitombo, L.M.; Cantarella, H.; Packer, A.P.C.; Ramos, N.P.; Do Carmo, J.B. Straw preservation reduced total N₂O emissions from a sugarcane field. *Soil Use Manag.* **2017**, *33*, 583–594. [[CrossRef](#)]
18. Zhang, W.; Zhou, G.W.; Li, Q.; Liao, N.; Guo, H.J.; Min, W.; Ma, L.J.; Ye, J.; Hou, Z.A. Saline water irrigation stimulate N₂O emission from a drip-irrigated cotton field. *Acta Agric. Scand. Sect. B-Soil Plant Sci.* **2016**, *66*, 141–152. [[CrossRef](#)]
19. Ghosh, U.; Thapa, R.; Desutter, T.; Yangbo, H.; Chatterjee, A. Saline–sodic soils: Potential sources of nitrous oxide and carbon dioxide emissions? *Pedosphere* **2017**, *27*, 65–75. [[CrossRef](#)]
20. Maucieri, C.; Zhang, Y.; McDaniel, M.D.; Borin, M.; Adams, M.A. Short-term effects of biochar and salinity on soil greenhouse gas emissions from a semi-arid Australian soil after re-wetting. *Geoderma* **2017**, *307*, 267–276. [[CrossRef](#)]
21. Zou, Q.H.; Ren, S.M.; Yang, P.L.; Niu, Y.T.; Zou, T. Effects of reclaimed water irrigation and brackish water irrigation on soil greenhouse gas emissions. *J. Irrig. Drain.* **2014**, *33*, 80–82. [[CrossRef](#)]
22. Zhang, L.H.; Song, L.P.; Wang, B.C.; Shao, H.B.; Zhang, L.W.; Qin, X.C. Co-effects of salinity and moisture on CO₂ and N₂O emissions of laboratory-incubated salt-affected soils from different vegetation types. *Geoderma* **2018**, *332*, 109–120. [[CrossRef](#)]
23. Azam, F.; Müller, C. Effect of sodium chloride on denitrification in glucose amended soil treated with ammonium and nitrate nitrogen. *J. Plant Nutr. Soil Sci.* **2003**, *166*, 594–600. [[CrossRef](#)]
24. Kontopoulou, C.K.; Bilalis, D.; Pappa, V.A.; Rees, R.M.; Savvas, D. Effects of organic farming practices and salinity on yield and greenhouse gas emissions from a common bean crop. *Sci. Hort.* **2015**, *183*, 48–57. [[CrossRef](#)]
25. Inubushi, K.; Barahona, M.A.; Yamakawa, K. Effects of salts and moisture content on N₂O emission and nitrogen dynamics in Yellow soil and Andosol in model experiments. *Biol. Fertil. Soils* **1999**, *29*, 401–407. [[CrossRef](#)]

26. Wang, S.J.; Yang, P.L.; Su, Y.P.; Shang, F.Z.; Wei, C.C.; Ren, S.M. Effects of alternative irrigation between brackish water and fresh water on CO₂ and N₂O emission from spring maize soil. *J. China Agric. Univ.* **2018**, *23*, 41–48. [[CrossRef](#)]
27. Wang, X.M.; Liu, H.J.; Zhang, L.W.; Zhang, R.H. Climate change trend and its effects on reference evapotranspiration at Linhe Station, Hetao Irrigation District. *Water Sci. Eng.* **2014**, *7*, 250–266. [[CrossRef](#)]
28. Zhou, L.F.; He, J.Q.; Qi, Z.J.; Dyck, M.; Zou, Y.F.; Zhang, T.B.; Feng, H. Effects of lateral spacing for drip irrigation and mulching on the distributions of soil water and nitrate, maize yield, and water use efficiency. *Agric. Water Manag.* **2018**, *199*, 190–200. [[CrossRef](#)]
29. Li, J.G.; Qu, Z.Y.; Chen, J.; Wang, F.; Jin, Q. Effect of different thresholds of drip irrigation using saline water on soil salt transportation and maize yield. *Water* **2018**, *10*, 1855. [[CrossRef](#)]
30. Ren, Z.S.; Qu, Z.Y.; Li, Z.; Liu, A.Q. Interactive effects of nitrogen fertilization and irrigation on grain yield, water use efficiency and nitrogen use efficiency of mulched drip-irrigated maize in Hetao Irrigation District, China. *J. Soil Water Conserv.* **2016**, *30*, 149–155. [[CrossRef](#)]
31. Qi, Y.L.; Shi, H.B.; Li, R.P.; Zhao, J.D.; Feng, Y.Y. The effects of water and nitrogen coupling on photosynthetic characteristics under mulched drip irrigation. *Water Sav. Irrig.* **2017**, *42*, 50–52.
32. Ma, Z.W.; Gao, X.P.; Tenuta, M.; Kuang, W.N.; Gui, D.W.; Zeng, F.J. Urea fertigation sources affect nitrous oxide emission from a drip-fertigated cotton field in northwestern China. *Agric. Ecosyst. Environ.* **2018**, *265*, 22–30. [[CrossRef](#)]
33. Han, B.; Ye, X.H.; Li, W.; Zhang, X.C.; Zhang, Y.L.; Lin, X.G.; Zou, H.T. The effects of different irrigation regimes on nitrous oxide emissions and influencing factors in greenhouse tomato fields. *J. Soils Sediments* **2017**, *17*, 2457–2468. [[CrossRef](#)]
34. Wang, G.S.; Liang, Y.P.; Zhang, Q.; Jha, S.K.; Gao, Y.; Shen, X.J.; Sun, J.S.; Duan, A.W. Mitigated CH₄ and N₂O emissions and improved irrigation water use efficiency in winter wheat field with surface drip irrigation in the North China Plain. *Agric. Water Manag.* **2016**, *163*, 403–407. [[CrossRef](#)]
35. Ding, J.J.; Fang, F.L.; Lin, W.; Qiang, X.J.; Xu, C.Y.; Mao, L.L.; Li, Q.Z.; Zhang, X.M.; Li, Y.Z. N₂O emissions and source partitioning using stable isotopes under furrow and drip irrigation in vegetable field of North China. *Sci. Total Environ.* **2019**, *665*, 709–717. [[CrossRef](#)]
36. Yin, G.F.; Wang, X.F.; Du, H.Y.; Shen, S.Z.; Liu, C.R.; Zhang, K.Q.; Li, W.C. N₂O and CO₂ emissions, nitrogen use efficiency under biogas slurry irrigation: A field study of two consecutive wheat-maize rotation cycles in the North China Plain. *Agric. Water Manag.* **2019**, *212*, 232–240. [[CrossRef](#)]
37. Feng, G.X.; Zhang, Z.Y.; Wan, C.Y.; Lu, P.R.; Bakour, A. Effects of saline water irrigation on soil salinity and yield of summer maize (*zea mays* L.) in subsurface drainage system. *Agric. Water Manag.* **2017**, *193*, 205–213. [[CrossRef](#)]
38. Karlberg, L.; Rockström, J.; Annandale, J.G.; Steyn, J.M. Low-cost drip irrigation—A suitable technology for southern Africa? An example with tomatoes using saline irrigation water. *Agric. Water Manag.* **2007**, *89*, 59–70. [[CrossRef](#)]
39. McNeal, B.L.; Coleman, N.T. Effect of solution composition on soil hydraulic conductivity. *Soil Sci. Soc. Am. J.* **1966**, *30*, 308–312. [[CrossRef](#)]
40. Oster, J.D.; Schroer, F.W. Infiltration as Influenced by irrigation water quality. *Soil Sci. Soc. Am. J.* **1979**, *43*, 444–447. [[CrossRef](#)]
41. Scheer, C.; Wassmann, R.; Kienzler, K.; Ibragimov, N.; Eschanov, R. Nitrous oxide emissions from fertilized, irrigated cotton (*Gossypium hirsutum* L.) in the Aral Sea Basin, Uzbekistan: Influence of nitrogen applications and irrigation practices. *Soil Biol. Biochem.* **2008**, *40*, 290–301. [[CrossRef](#)]
42. Chen, H.; Hou, H.J.; Wang, X.Y.; Zhu, Y.; Qaisar, S.; Wang, Y.F.; Cai, H.J. The effects of aeration and irrigation regimes on soil CO₂ and N₂O emissions in a greenhouse tomato production system. *J. Integr. Agric.* **2018**, *17*, 449–460. [[CrossRef](#)]
43. Zeng, W.Z.; Xu, C.; Wu, J.W.; Huang, J.S.; Ma, T. Effect of salinity on soil respiration and nitrogen dynamics. *Ecol. Chem. Eng. Sci.* **2013**, *20*, 519–530. [[CrossRef](#)]
44. Menyailo, O.V.; Stepanov, A.L.; Umarov, M.M. The transformation of nitrous oxide by denitrifying bacteria in Solonchaks. *Eurasian Soil Sci.* **1997**, *30*, 178–180.
45. Heincke, M.; Kaupenijohann, M. Effects of soil solution on the dynamics of N₂O emissions: A review. *Nutr. Cycl. Agroecosystems* **1999**, *55*, 133–157. [[CrossRef](#)]
46. Chen, H.; Hou, H.J.; Cai, H.J.; Zhu, Y. Soil N₂O emission characteristics of greenhouse tomato fields under aerated irrigation. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 111–117. [[CrossRef](#)]

47. Nishimura, S.; Komada, M.; Takebe, M.; Yonemura, S.; Kato, N. Nitrous oxide evolved from soil covered with plastic mulch film in horticultural field. *Biol. Fertil. Soils* **2012**, *48*, 787–795. [[CrossRef](#)]
48. Zhu, C.L.; Lv, W.; Huang, M.Y.; Zhai, Y.M.; Qiang, C. Effects of biochar on coastal reclaimed soil salinity distribution and maize growth with cycle fresh and saline water irrigation. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 227–234. [[CrossRef](#)]
49. Zhu, C.L.; Qiang, C.; Huang, M.Y.; Zhai, Y.M.; Lv, W. Effect of alternate irrigation with fresh and slight saline water on physiological growth of summer maize in coastal reclamation area. *Trans. Chin. Soc. Agric. Mach.* **2018**, *49*, 253–261. [[CrossRef](#)]
50. Munns, R. Physiological processes limiting plant growth in saline soils: Some dogmas and hypotheses. *Plant Cell Environ.* **2010**, *16*, 15–24. [[CrossRef](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).