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Yield-compatible salinity level for growing cotton (*Gossypium hirsutum* L.) under mulched drip irrigation using saline water

Futian Ren[a,b], Guang Yang[a,b,c,*], Wanjing Li[a,b], Xinlin He[a,b,*], Yongli Gao[c], Lijun Tian[d], Fadong Li[e,f], Zelin Wang[a,b], Saihua Liu[a,b]

[a] College of Water and Architectural Engineering, Shihezi University, Shihezi, China
[b] Xinjiang Production and Construction Group Key Laboratory of Modern Water-Saving Irrigation, Shihezi, China
[c] Department of Geological Sciences, Center for Water Research, University of Texas at San Antonio, TX, United States
[d] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[e] Institute of Geographic Sciences and Natural Resources Research, Beijing, China
[f] University of Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Mulched drip irrigation using saline water has the potential to alleviate pressure on crop production from limited freshwater resources in arid and semi-arid regions. To explore the potential of saline water irrigation, it is necessary to investigate how salt stress caused by saline water irrigation affects soil physico-chemical properties and the physiology and growth of crops. The effects of salt stress caused by saline water irrigation are complex and, to date, they are not well understood. We aimed to analyse the distribution and dynamics of these properties to assess their effects on cotton growth, yield, and water productivity during a two-year field experiment using saline water irrigation with various salinity levels (1, 3, 6, 9, and 12 g L^{-1}). Cotton yield, water productivity, and their related components were significantly affected by the different salinity levels. (1) Irrigation water-derived salt accumulated in the soil, especially in the surface soil layer (0–20 cm), but not in the 60–80 cm layer. It was possible to rank cotton main root length based on salinity level as follows: 3 > 1 > 6 > 9 > 12 g L^{-1}. (2) During the growth stage, plants in the 3 g L^{-1} salinity treatment had transpiration rates [1]0–30% higher, net photosynthetic rates 20–40% higher, and yields 25–55% higher than those in the other treatments. (3) The 3 g L^{-1} salinity treatment provided the optimal watering conditions for cotton, and plants in this treatment displayed no salt stress symptoms in terms of their physiology or growth. Therefore, this salinity level is suitable for the mulched drip irrigation of cotton using saline water. Our research provides guidance for further exploitation and utilisation of brackish and saline water resources and sustainable development of irrigated agriculture in semi-arid and arid areas.

1. Introduction

Fresh water shortages and soil salinisation are the two primary factors limiting sustainable agriculture in many semi-arid and arid regions worldwide. The exploitation and utilisation of saline water resources have the potential to alleviate the ongoing freshwater shortages (Grillot, 1954; Pasternak et al., 1986; Rahman et al., 2015). Cotton (*Gossypium hirsutum* L.) is a salt-tolerant crop that requires ample light (Christianson et al., 2010; Liu et al., 2012; Wang et al., 2014; Ning et al., 2015). Xinjiang is located in the hinterlands of northwest China and has a typical dry continental climate (Yang et al., 2020a). This area is suitable for cotton growth, as the growing conditions are optimal for high dry matter accumulation and high-quality long fibre growth. The Xinjiang cotton production area constitutes 30% of the total global area devoted to cotton, and it produces 75% of the Chinese cotton output. In the past few decades, mulched drip irrigation, which can increase soil moisture and prevent soil secondary salinisation, has been widely implemented in cotton cultivation in Xinjiang, to combat drought and water shortages. An underground saline water resource in this region is gradually starting to be used to meet the increasing irrigation demands (Shen and Lein, 2005; Yang et al., 2019; Mansour et al., 2019a, 2019b; Chen et al., 2020).

* Corresponding authors at: College of Water and Architectural Engineering, Shihezi University, Shihezi, China
E-mail addresses: renfutiann@163.com (F. Ren), mikeyork@163.com (G. Yang), 13795665928@163.com (W. Li), hexinlin2002@163.com (X. He), yongli.gao@utsa.edu (Y. Gao), tianlijun@mail.iggcas.ac.cn (L. Tian), lifadong@igsnrr.ac.cn (F. Li), 1821729975@qq.com (Z. Wang), lsh004031@163.com (S. Liu).

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Saline water irrigation can result in salt stress to plants, physiological drought, reduced soil oxygen content, anaerobic respiration by roots, and accumulation of toxic substances (Bouksila et al., 2013). The correct balance of salt and water in the soil is central to successful crop growth. Increasing salt stress causes membrane lipid peroxidation, protein oxidation, and other damage to lipids, proteins, and nucleic acids, leading to abnormal plant metabolism. Initial chlorophyll fluorescence is also reduced, as are the maximum photochemical efficiency and maximum net photosynthetic rate (Zhang et al., 2006; Pang et al., 2010). Excess salt affects root water absorption, photosynthesis, and transpiration. This leads to growth inhibition of roots, stems, leaves, and other organs and reduces dry matter production, ultimately leading to a reduction in crop yield (Parida et al., 2005).

Stomata are the main channels for the exchange of CO_2 and O_2, and the escape of water vapour from leaves (Maas and Hoffman, 1977; Wu et al., 2014). They use variable opening to regulate these transport processes, thereby controlling leaf photosynthetic and transpiration rates (Guo et al., 2005; Rahman et al., 2015; Zhang et al., 2006). The photosynthetic rate affects the roots, stems, leaves, fruits, and other plant organs, and, is therefore related to crop yield. Transpiration inevitably leads to water loss, affecting crop photosynthesis, and its rate has an important effect on available water resources and agricultural water utilisation efficiency (Yang et al., 2015; Ghaderi et al., 2012; Kang et al., 2012; Singh et al., 2010).

Cotton can adapt to drought, to a certain degree (Pettigrew, 2004). However, when under salt stress, cotton growth is inhibited, and plant height gain is significantly slowed. This results in shorter plants grown under full irrigation (Liu et al., 2012). Salt stress can also affect the morphology and distribution of root growth and affect the ability of roots to absorb water and nutrients. Salt stress at the seedling stage promotes the growth of the main root and increases the number of lateral roots (Yazar et al., 2002). Moreover, salt stress can inhibit the production of bolls and promote boll abscission, resulting in reduced cotton yields. On the one hand, using saline water for agricultural irrigation can provide the necessary amount of water for crop growth, but, on the other hand, saline water increases the accumulation of salt in the soil, which negatively affects soil conditions and crop yield (Chen et al., 2010).

However, many factors remain unclear, such as 1) what is the appropriate irrigation water salinity level for cotton that ensures optimal yield and water productivity (WP) under saline water mulched drip irrigation; and 2) what are the effects of different irrigation salinity levels on soil physico-chemical properties, and cotton physiological and biochemical processes and growth indices (including the main root length, leaf area index, and dry mass accumulation)?

To answer these questions, we conducted a two-year growing season field experiment to evaluate saline water utilisation by cotton under mulched drip irrigation. The main objectives of this study were to 1) assess the effect of different water salinity levels, applied via mulched drip irrigation, on the soil salinity balance within the root zone; 2) measure the effects of different water salinity levels on cotton growth, physiological and biochemical processes, yield, and WP; and 3) to determine the most suitable yield-compatible salinity level for mulched drip irrigation using saline water, to guide the sustainable development of future irrigation schemes and water resource utilisation planning for cotton production within semi-arid and arid regions.

2. Material and methods

2.1. Experimental site description

This study was conducted, during the two consecutive cotton growing seasons of 2018 and 2019, in a cotton field at the Xinjiang Production and Construction Group Key Laboratory of Modern Water-Saving Irrigation (44° 19′ 30′ N, 85° 59′ 53′ E; 412 m above sea level) in Shihezi, Xinjiang, China (Yang et al., 2020a). The experimental area was located in the Manas River Basin alluvial plain, which is an inland arid area with a typical continental climate (Yang et al., 2020b). The long-term annual precipitation is only 125.0–207.7 mm, the annual evaporation range is 1 500–2 100 mm, and the drought index range is 15–25. The annual average temperature ranges from 7.9° to 8.7 °C, the accumulated temperature range above 0 °C is 4 023–4 118 °C, the average annual sunshine duration is 2 865 h, and the frost-free period lasts between 168 and 171 days (Yang et al., 2017a). The groundwater levels in the experiment plots during both the 2018 and 2019 cotton growing seasons were below 9 m. The soil is a silty loam with a bulk density of 1.51 g cm^{-3}, the field capacity is 19.13%, and the permanent wilting point is 5.00% (Supplementary Material 1). The daily average temperature, evaporation, and precipitation data collected from a small automatic weather station (Watchdog 2700, Spectrum Technologies Inc., USA) during the experiment are shown in Fig. 1.

2.2. Experimental design and treatments

This research was conducted in 15 experimental plots (each 3 × 2 m). Adjacent plots were separated by 10 cm to eliminate soil water lateral seepage. Each plot was excavated to a depth of 200 cm and a 30 cm-thick filter layer was placed at the bottom (further details about the experimental plots are provided in Supplementary Material 2). Five treatments with three replicates each were arranged in a randomised block design. All treatments consisted of mulched drip irrigation with different water salinities: A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

The study plant was the Nongfeng No. 133 cotton variety, which is grown widely in the local area. Plants were seeded at a density of 21 seeds m^{-2} under mulched drip irrigation. A 'one mulch, two drip pipes, and four crop rows' pattern (Fig. 2) was followed, which is the main cultivation pattern used locally in cotton crop management. The chemical composition of the saline water (at the different salinity levels used in this irrigation experiment) was based on groundwater quality data from a local deep well which is the main source of irrigation in the study area. We configured the different irrigation water salinity levels using $NaHCO_3$, Na_2SO_4, NaCl, $CaCl_2$, and $MgCl_2$ at a mass ratio of 1:7:8:1:1 (Yang et al., 2020a). The mulched drip irrigation schedule used during the study period followed the traditional mode used in the study area (Table 1). Each drip irrigation period continued for 4–6 h, and the flow rate of the drip pipes was 2.4 L h^{-1}. During the whole cotton growth period, irrigation was performed nine times, and the irrigation intervals of the field experiment were 6–20 days. The detailed irrigation schedules are shown in Table 1. The operation pressure, provided by a submerged pump, was 0.09 MPa. The drippers on each drip line were spaced 30 cm apart and the cotton plants in each row were spaced 10 cm apart. All measurements and treatments remained identical throughout the experiment (in both 2018 and 2019).

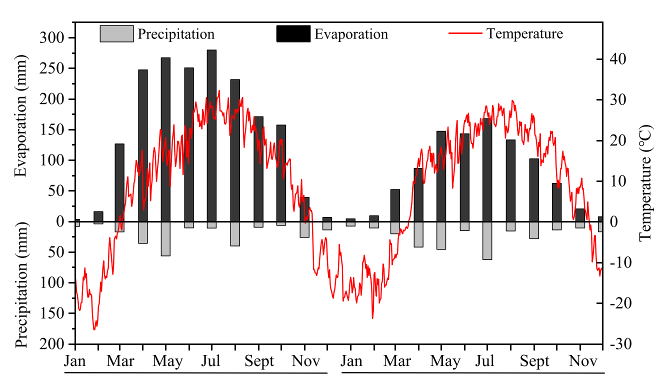

Fig. 1. Meteorological data for the study area in 2018 and 2019 (including temperature, precipitation, and evaporation).

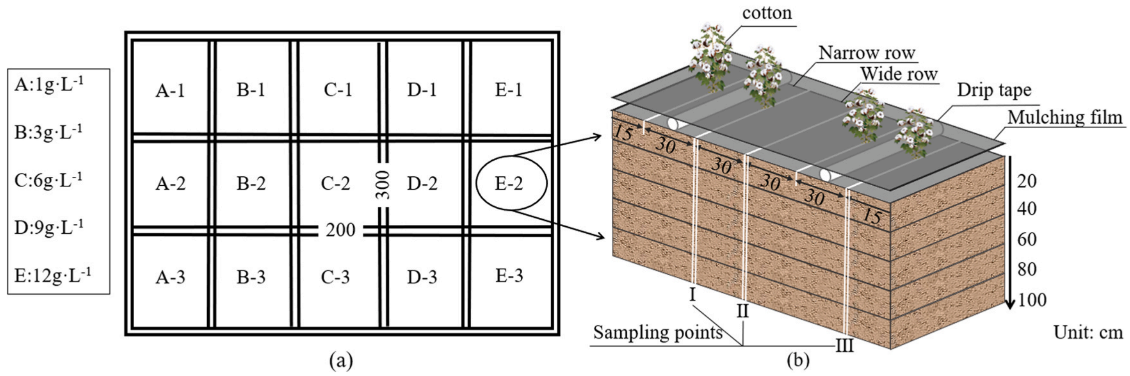

Fig. 2. (a) The layout of the experimental plots and (b) a vertical profile map of the experimental plots and sampling sites (from I to III) in the plots, in which location I and III are located at the two sides of narrow row zone, II is located at the middle of wide row zone.

Table 1
Schedule and amount of irrigation water implemented during the whole growth period. Both saline water irrigation treatments had the same water quantities for all years.

Growth stage	Date	DAS	Irrigation quota (mm)	Date	DAS	Irrigation quota (mm)
Squaring	20 May.	25	52.7	18 May.	25	52.7
	10 Jun.	45	53.4	08 Jun.	45	53.4
Flowering	25 Jun.	60	53.4	23 Jun.	60	53.4
	05 Jul.	75	53.4	03 Jul.	75	53.4
	11 Jul.	81	53.4	09 Jul.	81	53.4
Bolling	21 Jul.	92	53.4	19 Jul.	92	53.4
	01 Aug.	104	53.4	30 Aug.	104	53.4
	09 Aug.	112	53.4	09 Aug.	115	53.4
Boll opening	16 Aug.	120	53.4	18 Aug.	125	53.4
Total quota			479.8			479.8

* DAS: days after sowing

2.3. Data collection

2.3.1. Soil moisture and electrical conductivity

Soil samples were collected from each plot at depths of 20 cm and from 0 to 100 cm, using an auger (5 cm diameter, 100 cm height) before irrigation days. Samples of 10 g of fresh soil were weighed to measure the moisture content using the oven drying method (105 °C, 24 h). Average values were calculated from three replicates taken from each soil sample.

The soil samples were air-dried and pulverised until they could pass through a 1-mm sieve. Then, soil electrical conductivity (EC) was determined in mixtures of dried soil and ultrapure water at a ratio of 1:5 (by weight), using a conductivity meter (DDS-11A, Ningbo Biocotek Scientific Instrument Co., Ningbo, China). The soil pH of each sample extract was measured by potentiometry using a glass electrode.

2.3.2. Hydro-chemical ions

The main anions (Cl^- and SO_4^{2-}) were determined using an ion chromatograph (ICS-900 Starter Line IC System, USA), and the main cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were determined using an inductively coupled plasma emission spectrometer (ICP-OES, iCAP™ PRO, USA). Levels of HCO_3^- and CO_3^{2-} were measured using a double indicator-neutralisation titration (methyl orange and phenolphthalein).

2.3.3. Plant physiological data

Three plants were randomly selected from each experimental plot during the growth period, which is when cotton produces branches and leaves. Photosynthetic parameters were measured using an LCpro+ portable photosynthesis system (ADC Bioscientific Ltd., UK). Measurements were taken between 08:00 and 18:00 at intervals of 2 h. The parameters measured included the net transpiration rate (Tr), photosynthetic rate (Pn), stomatal conductance (Gs), and intercellular CO_2 concentration (Ci). During measurement, the canopy of each cotton plant was divided into the upper, middle, and lower leaf layers. Two sun leaves were selected from each leaf layer, and each sun leaf was measured five times. The measurements across the whole day were averaged for each treatment.

The leaf chlorophyll maximum fluorescence (Fm) and the initial fluorescence (Fo) were determined using a PAM-2500 portable fluorometer (Walz, Germany). Three representative plants were selected from each treatment, and three mature leaves from the upper, middle, and lower parts of each plant were selected to obtain an average value. The variable fluorescence (Fv) was calculated as the difference between Fm and Fo. The maximum potential activity of PS II (Fv/Fo) and the photochemical efficiency (Fv/Fm) were also calculated.

2.3.4. Cotton growth

The main root length was measured using a tape measure and the length and width of the blade were measured using Vernier callipers. The leaf area index (LAI) was calculated as follows:

$$LAI = 0.75 \times L \times W \times K \quad (1)$$

where L is the vein length (m), W is the maximum width (m), and K is the cotton planting density (plants m^{-2}).

2.3.5. Dry matter yield and cotton yield

The roots, stems, and leaves of three representative cotton plants from each experimental plot were collected, washed with deionised water, and dried at 105 °C for 30 min and then at 75 °C to achieve a constant weight. Samples were then weighed using an electronic balance (accurate to 0.01 g) to determine their dry weight. The cotton yield was obtained by harvesting the cotton and calculating the yield per unit area (kg ha^{-1}).

2.3.6. WP

The WP was determined as follows:

$$WP = Y / ET, \quad (2)$$

where Y is the cotton yield (kg ha^{-1}), and ET is the cotton water consumption (mm) (Hussain and Al-Jaloud, 1995). Surface runoff, groundwater recharge, and deep leakage were not measured in this study (Andreu et al., 1997). We, therefore, calculated ET as follows:

$$\mathrm{ET} = I + P + \Delta SWS, \quad (3)$$

where I is the field irrigation quota (mm), P is the precipitation during the growth period (mm), and ΔSWS is the variation in moisture content from sowing to harvest. During the cotton growing seasons in 2018 and 2019, total precipitation was 104.1 mm and 92.1 mm, respectively.

2.4. Statistical analysis

Variance analysis was carried out using the SPSS 24.0 package (SPSS Inc., Chicago, USA). Tukey's significant difference test was used to determine significant differences between the salinity treatments at $P < 0.05$. The figures were created using OriginPro 2020b (OriginLab, USA).

3. Results

3.1. Soil pH

Variations in soil pH under different salinity treatments are shown in Fig. 3. The soil pH followed a curved pattern across the entire growth period, culminating in a single peak at the flowering stage in 2018. In general, the soil pH increased with increasing salinity. However, the average pH was higher in treatment A than in treatments B, C, or D (by 4.2%, 2.5%, and 2.5%, respectively). The average pH in treatment A was lower than that in treatment E by 0.8%, but there was no significant difference between A and E.

3.2. Soil moisture and EC

The vertical distribution of soil moisture in the different soil layers under each treatment during 2018 and 2019 are shown in Fig. 4. Soil moisture fluctuated within the 0–100 cm soil layer. In the 0–20 cm layer, the observed soil moisture was 5–15%. This large range may be a result of precipitation and the associated intense evaporation that follows. Soil moisture was high in the 20–80 cm layer, in which the cotton root system is mainly distributed. Water consumption by cotton was high, and the resulting change in soil moisture was clear. In the 80–100 cm layer, soil moisture levels were at their lowest for the duration of the experiment. The soil moisture levels in the different salinity treatments were ordered as follows: E > D > C > B> A. Root water absorption was restricted in the higher-salinity (>6 g L^{-1}) treatments, while plants in the lower-salinity treatments (A and B) had improved root water absorption.

Fig. 5 shows the distribution of soil EC at different soil depths. Soil salinity increased slightly during the growth period, particularly in the 0–20 cm surface soil layer. However, a reduction in salinity was observed in the 60–80 cm soil layer. The soil EC range within the different treatments was 0.30–2.38 mS cm^{-1}, with most values close to or greater than 1.5 mS cm^{-1}. During the squaring stage in 2018, the experimental plots were first irrigated with saline water, and the EC values measured at this stage were assigned as the EC background values representing long-term mulched drip irrigation with fresh water. As the growth period progressed, the soil EC of each treatment was found to develop into a single-peaked curve. Soil EC levels also varied with depth in the 0–100 cm sampling zone. The maximum values of all treatments (A, B, C, D, and E) were observed in the 0–20 cm layer during the boll-opening stage in 2018 (1.30, 1.72, 2.01, and 2.10 mS cm^{-1}, respectively). The minimum EC values occurred in the 60–80 cm layer during the flowering stage in 2018 (0.53, 0.38, 0.72, 0.71, and 0.34 mS cm^{-1}, respectively).

3.3. Soil hydro-chemical characteristics

Piper diagrams were used to illustrate the hydro-chemical species observed in the soil samples from the different salinity treatments in 2018 and 2019 (Fig. 6). In all treatments in both years, the Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and HCO_3^- concentrations were higher than those of the other ions measured. The two main cations accounted for 50–80% of the milligram equivalent, and the three anions accounted for 80–100%. From 2018–2019, the main hydro-chemical species in treatment A evolved from SO_4^{2-}-Ca^{2+} to SO_4^{2-}-Mg^{2+}•Ca^{2+}. Similarly, in treatment B, SO_4^{2-}• HCO_3^--Ca^{2+}•Mg^{2+} evolved into SO_4^{2-}-Ca^{2+}•Mg^{2+}. In treatment C, SO_4^{2-}-Ca^{2+} evolved to SO_4^{2-}• Cl^--Ca^{2+}•Mg^{2+}. In treatment D, SO_4^{2-}-Ca^{2+}•Mg^{2+} evolved into SO_4^{2-}• Cl^--Ca^{2+}•Mg^{2+}•Na^+. Finally, in treatment E, SO_4^{2-}• Cl^--Ca^{2+}•K^+ evolved into SO_4^{2-}-Ca^{2+}•Mg^{2+}. As salinity increased, the milligram equivalent of anions gradually evolved from Ca^{2+} to Mg^{2+} and Na^+, and the cations gradually evolved from SO_4^{2-} to Cl^-. This was the main reason that the soil water hydro-chemical species evolved from SO_4^{2-}-Ca^{2+} to SO_4^{2-}•Cl^--Ca^{2+}•Mg^{2+}•Na^+.

3.4. Net photosynthetic rate and transpiration rate

The Pn of cotton varied throughout the 2018 growth period and followed a double-peaked curve which reached its highest points during the flowering and bolling stages. However, in 2019, the Pn followed a single-peaked curve which reached its highest point during the flowering stage (Fig. 7). Treatment B showed the highest Pn values in all growth stages. During boll setting, the Pn values of the plants in treatment B were 8.2% and 10.9% higher in 2018 and 2019, respectively, than those in treatment A. In 2018, the Pn values of the plants in the high salinity C, D, and E treatments were 21.2%, 29.7%, and 40.7% lower, respectively, than those in treatment B, and they were 23.7%, 33.2%,

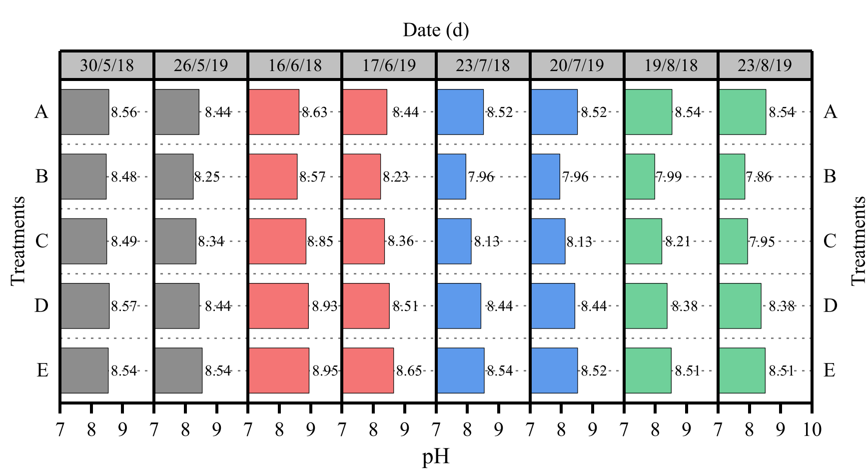

Fig. 3. Soil pH in different cotton growth stages under different irrigation water salinity treatments. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

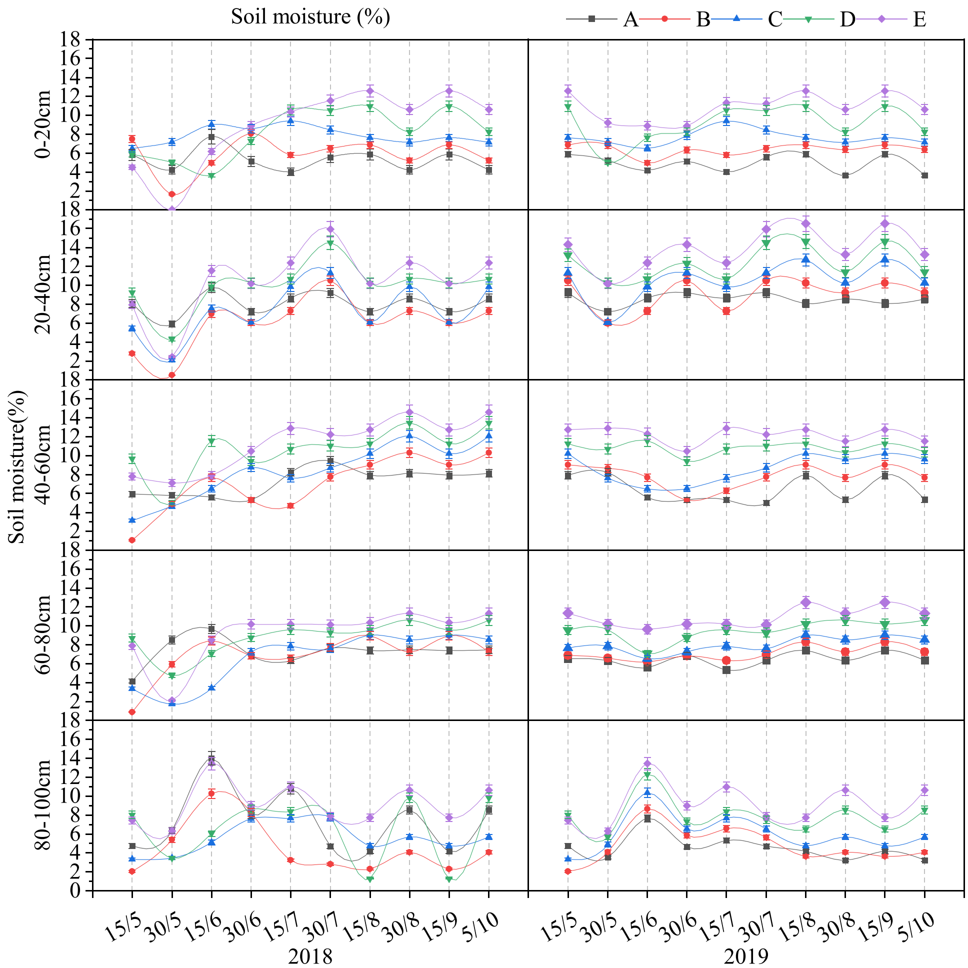

Fig. 4. Comparison of the vertical distribution of soil moisture (g g^{-1}) under different salinity treatments during the 2018 and 2019 growing seasons. Data (mean ± SD) were collected from 0 to 100 cm soil depths. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

and 42% lower, respectively, in 2019. During flower setting, the Pn values of the plants in treatment B were 9% and 8.8% higher than those in treatment A in 2018 and 2019, respectively. In 2018, the Pn values of the plants in treatments C, D, and E were 13.4%, 39.7%, and 58.9% lower than those in treatment B, respectively, and they were 11.7%, 38.5%, and 58.1% lower in 2019.

The Tr of cotton was not significantly affected by the irrigation water salinity level during any of the growth stages. The Tr gradually decreased as the cotton plants passed through each successive growth stages (Fig. 7). Compared to the other treatments, the treatment B plants had the highest Tr at each growth stage. During boll setting, the Tr values of the plants in treatment B were 5.1% and 11.1% higher than those in treatment A in 2018 and 2019, respectively. In 2018, the Tr values of the plants in treatment C, D, and E were 26.0%, 33.0%, and 38.3% lower than those in treatments B, respectively, and they were 26.0%, 32.9%, and 38.3% lower in 2019. During flower setting, the Tr values of the treatment B plants were 4.0% and 10.6% higher than those in treatment A in 2018 and 2019, respectively. In 2018, the Tr values in treatments C, D, and E were 9.9%, 21.1%, and 30.6% lower than those in treatment B, respectively, and they were 9.9%, 31.7%, and 30.5% lower in 2019.

3.5. Stomatal conductance and intercellular CO_2 concentration

Gs and Ci greatly affect photosynthesis in cotton leaves. Gs tends to decrease with increasing water salinity. The Gs values of the plants in treatment B were higher than those of any other treatments, across all growth stages (Fig. 8). The Gs of cotton plants was significantly affected by the different salinity levels in the treatments during the flowering stage. Compared to the Gs values in treatment B, those in treatments A, C, D, and E decreased by 6.1%, 38.5%, 46.2%, and 51.9%, respectively, in 2018, and by 9.1%, 47.0%, 52.0%, and 58.2%, respectively, in 2019. The Ci increased with increasing water salinity and the levels in each treatment followed the shape of a single-peaked curve throughout the two growing seasons. These curves reached their maximum points during the bolling stage (Fig. 8). During the bolling stage, the Ci values in treatment B were 27.5% and 21.2% high than those in treatment A in 2018 and 2019, respectively. Compared to the Ci values in treatment B, those in treatments C, D, and E increased by 5.2%, 7.8%, and 15.7%, respectively, in 2018, and by 5.3%, 8.5%, and 15.7%, respectively, in 2019.

3.6. Chlorophyll fluorescence

The Fo increased with increasing irrigation water salinity in all growth stages (Fig. 9). Following irrigation with saline water, the Fo of the plants in each treatment increased throughout the experiment. The Fo values of the plants in treatment E were higher than those in all the other treatments at each growth stage. However, regarding Fm, a contrasting result was observed. Fm decreased with increasing irrigation water salinity. The Fm values of the plants in treatment E were the lowest of all the treatments at each growth stage, and they reached their minimum values during the boll-opening stage. Throughout the growth stage in 2018, the Fo values of the plants in treatments B, C, D, and E

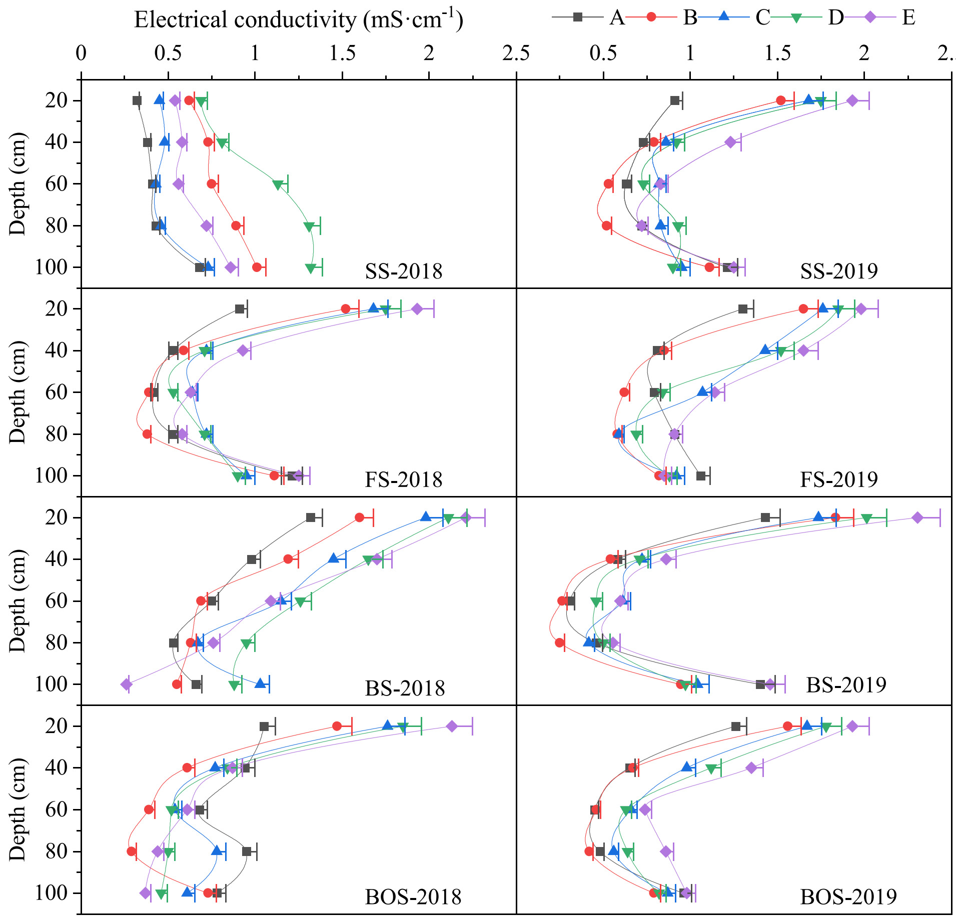

Fig. 5. Comparison of soil salinity levels under different salinity treatments during two growing seasons in 2018 and 2019. Data (average ± SD) were obtained from soil samples collected at depths of 0–100 cm. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

were 2.3%, 5.1%, 10.1% and 13.8% higher, respectively, than that in treatment A, and they were 1.6%, 5.2%, 14.4%, and 19.3% higher in 2019. In 2018, the Fm values of the plants in treatments B, C, D, and E were 7.2%, 15.9%, 23.9%, and 27.7% lower than that in treatment A, respectively, and they were 12.3%, 18.1%, 27.1%, and 40.5% lower in 2019.

The potential photosynthetic activity (Fv/Fo) and maximum photosynthetic efficiency (Fv/Fm) of PS II both decreased as irrigation water salinity increased (Fig. 10). Throughout the growth stage in 2018, the Fv/Fo values of the plants in treatments B, C, D, and E were 3.4%, 8.0%, 9.4%, and 19.3% lower, respectively, than that in treatment A, and they were 5.4%, 8.1%, 14.7%, and 22.8% lower in 2019. The Fv/Fm values of the plants in treatments B, C, D, and E were 6.6%, 19.4%, 26.2%, and 41.4% lower than that in treatment A in 2018, respectively, and they were 5.9%, 19.4%, 26.2%, and 41.4% lower in 2019.

3.7. Cotton growth index

The largest main root length and LAI were both significantly affected by the different salinity treatments. Both indices were highest in plants grown in treatment B compared to those in the other treatments throughout the two-year field experiment (Fig. 11). In addition, both indices were lower in plants from treatment E than in plants from any of the other treatments (Fig. 11). The main root system lengths of the plants in treatment B were 45.3% and 10.6% longer than those in treatment A in 2018 and 2019, respectively. The LAI values of the plants in treatment B were also 1.2% and 29.2% higher in 2018 and 2019, respectively, than those in treatment A. In 2018, the main root lengths of the plants in treatments C, D, and E were 25.8%, 44.1%, and 53.8% shorter, respectively, than those of the plants in treatment B, and they were 15.1%, 23.3%, and 30.1% shorter in 2019. In a similar comparison, the LAI values were 25.2%, 32.9%, and 65.1% shorter in 2018, respectively, and they were 39.7%, 68.2%, and 69.6% shorter in 2019, respectively.

Of all the treatments, the dry matter production of roots, stems, and leaves were highest in the plants from treatment B in both years (Fig. 12). The root dry matter production of the plants in treatment B was 10.1% and 12.7% higher than that of the plants in treatment A in 2018 and 2019, respectively. Comparing the same two treatments, stem dry matter was 5.8% and 22.9% higher in 2018 and 2019, respectively, and leaf dry matter was 1.7% and 3.2% higher in 2018 and 2019, respectively. In 2018, the root dry matter production of the plants in treatments C, D, and E was 13.8%, 15.2%, and 24.7% lower, respectively, than that of the plants in treatment B, and they were 17.8%, 20.9%, and 24.2% lower, respectively, in 2019. Stem dry matter production, in the same comparison of treatments (C, D, and E vs. B), was 21%, 28.6%, and 47.3% lower, respectively, in 2018, and 19.8%, 29.3%, and 41.3% lower, respectively, in 2019. Leaf dry matter production when comparing the same treatments was 10.5%, 25.7%, and 9.0% lower, respectively, in 2018, and 9.5%, 22.4%, and 26.3% lower, respectively, in 2019.

3.8. Cotton yield and WP

Cotton yield and WP were significantly affected by the different salinity treatments in both years (Fig. 13). Both indices decreased with increasing salinity. Yield and WP were higher in the plants grown in treatments A, B, and C than in those grown in the other treatments.

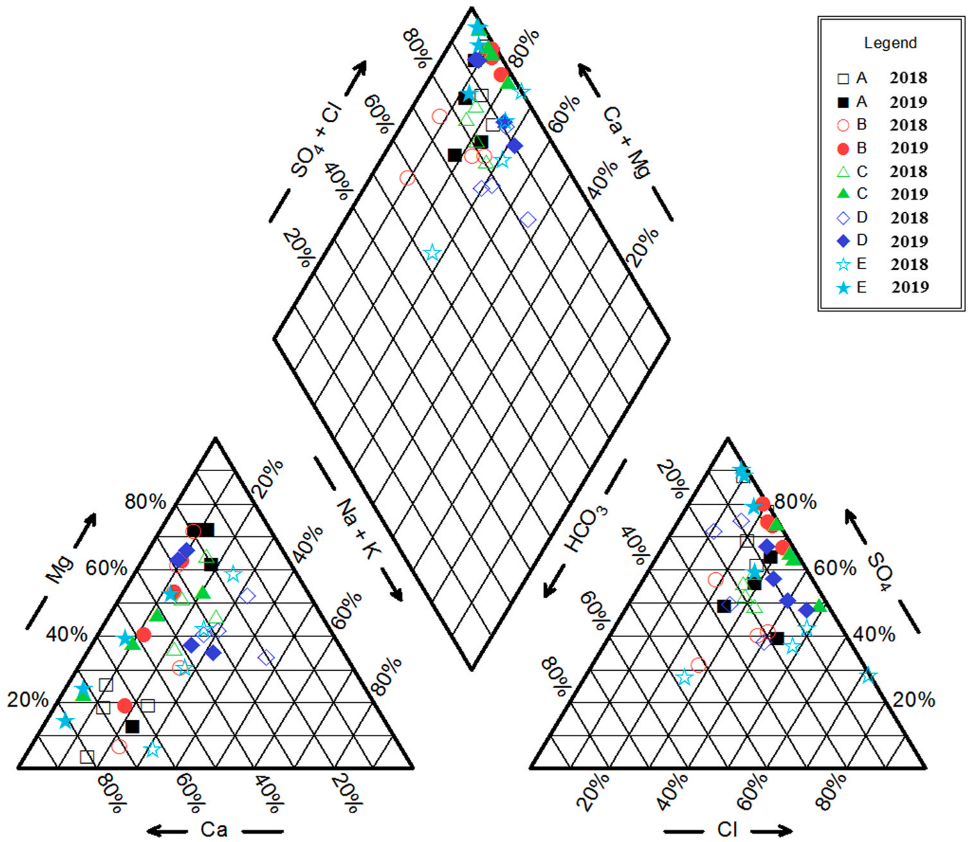

Fig. 6. Piper diagrams illustrating the hydro-chemical species observed in soil samples taken from different irrigation salinity treatments (A to E). A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

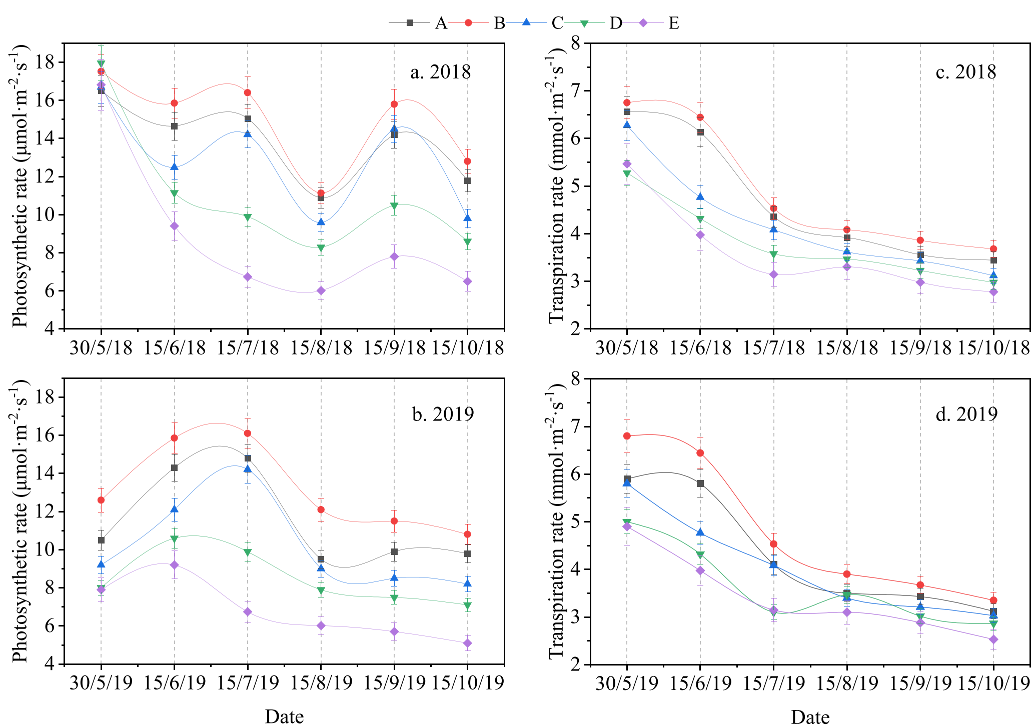

Fig. 7. Comparison of net photosynthetic rates (Pn) and transpiration rates (Tr) of cotton plants grown in different salinity treatments in a field experiment. Data (average ± SD) were collected at various cotton growth stages. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

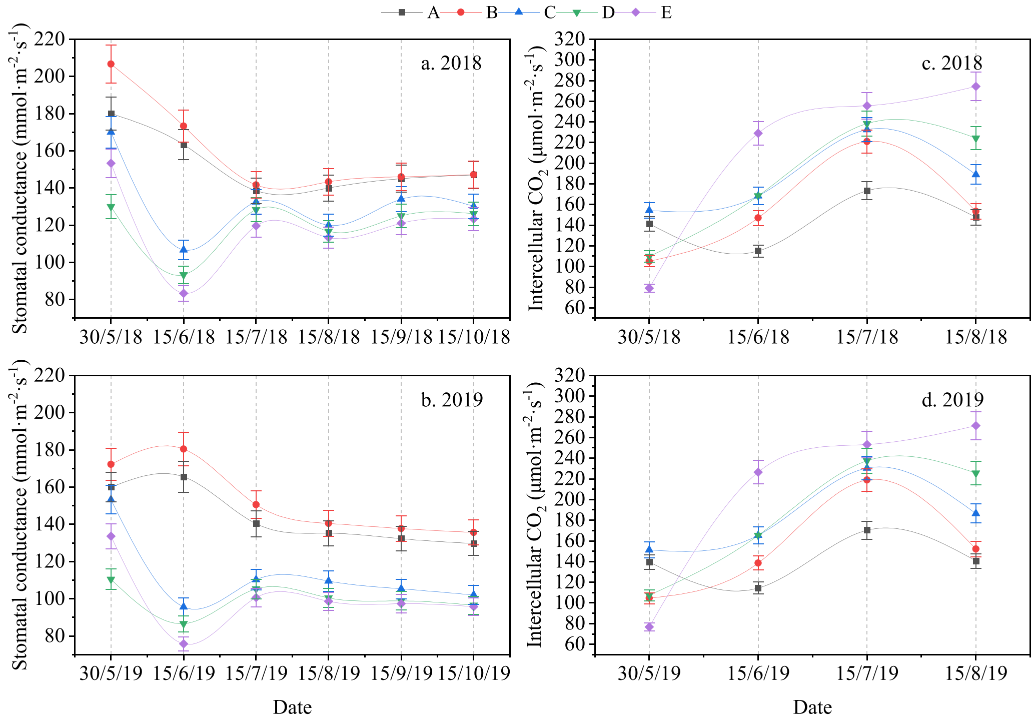

Fig. 8. Comparison of stomatal conductance (Gs) and intercellular CO_2 concentrations (Ci) in plants grown in different salinity treatments in a field experiment. Data (average ± SD) were collected during various growth stages. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

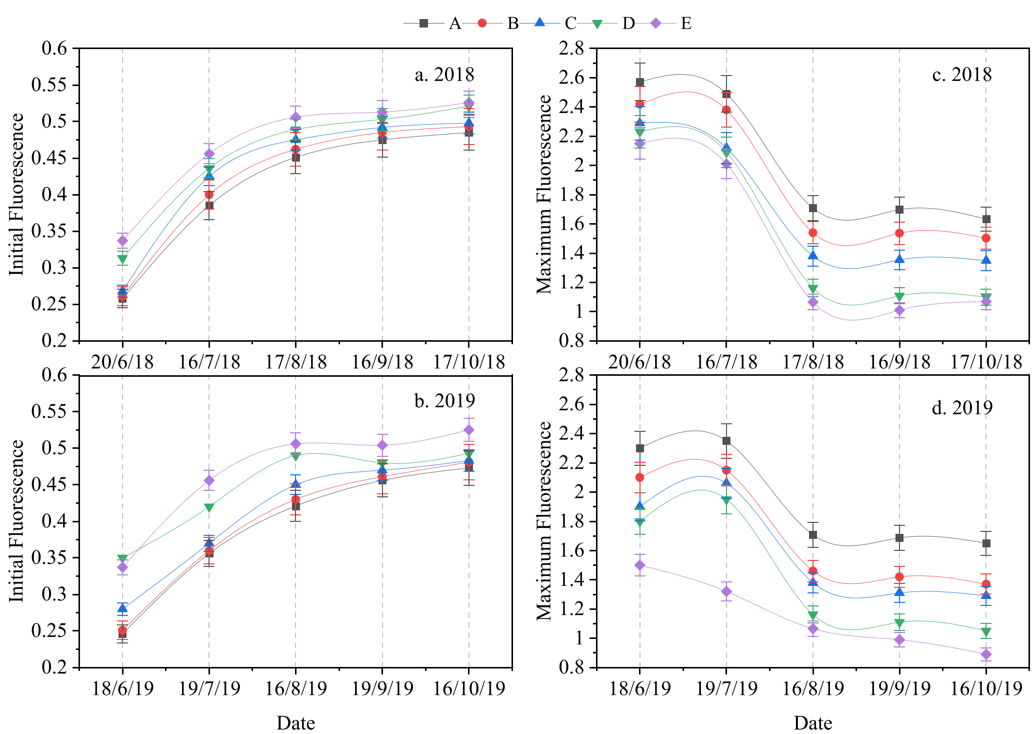

Fig. 9. Comparison of Initial Fluorescence (Fo) and Maximum Fluorescence (Fm) of cotton plants grown in different salinity treatments in a field experiment. Data (average ± SD) were collected at various cotton growth stages. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

When the salinity level was greater than 6 g L^{-1}, yield and WP were significantly negatively affected. When the cotton plants were exposed to salinity levels between 1 g L^{-1} and 6 g L^{-1}, yield and WP greatly increased. The yields of treatment B were 13.1% and 24.1% higher than those of treatment A in 2018 and 2019, respectively. Using the optimal irrigation water salinity level may therefore improve cotton yield. Finally, in 2018, the yields in treatments C, D, and E were 17.8%, 38.0%, and 55.6% lower, respectively, than that in treatment B, and they were 25.1%, 43.5%, and 60% lower, respectively, in 2019. The WP of the cotton grown in treatment B was the highest across all treatments, and it was 12.5% and 24% higher than that in treatment A in 2018 and 2019, respectively. Given that the plants were irrigated with saline water in

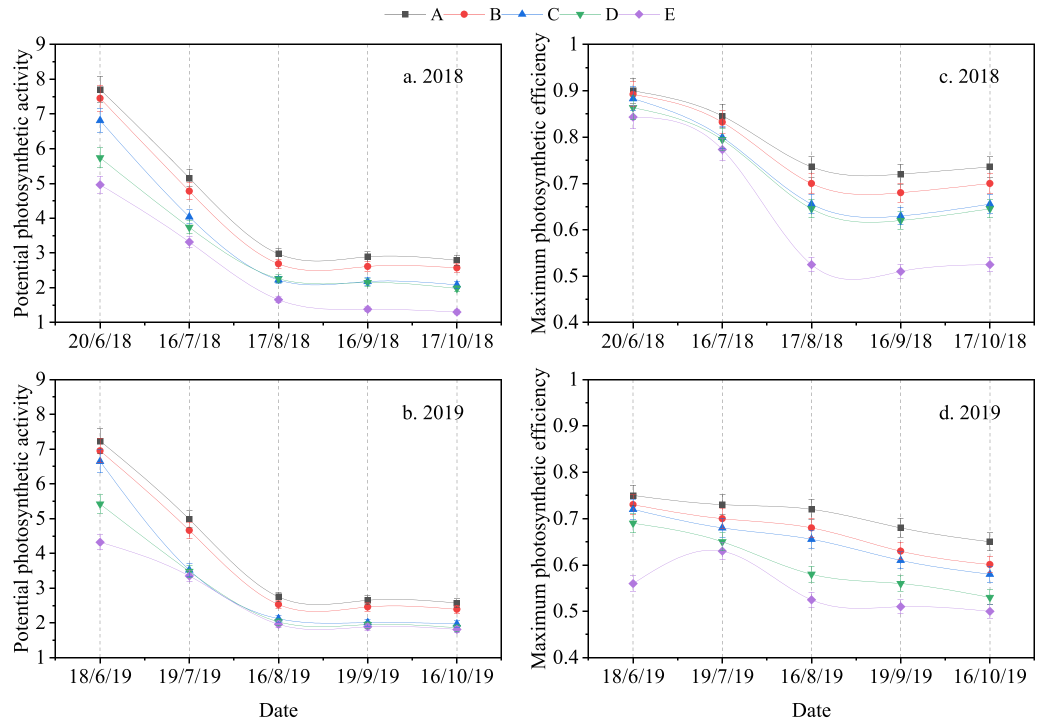

Fig. 10. Comparison of potential photosynthetic activity (Fv/Fo) and maximum photosynthetic efficiency (Fv/Fm) of PS II in plants grown in different salinity treatments in a field experiment. Data (average ± SD) were collected at various cotton growth stages. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, 12 g L^{-1}.

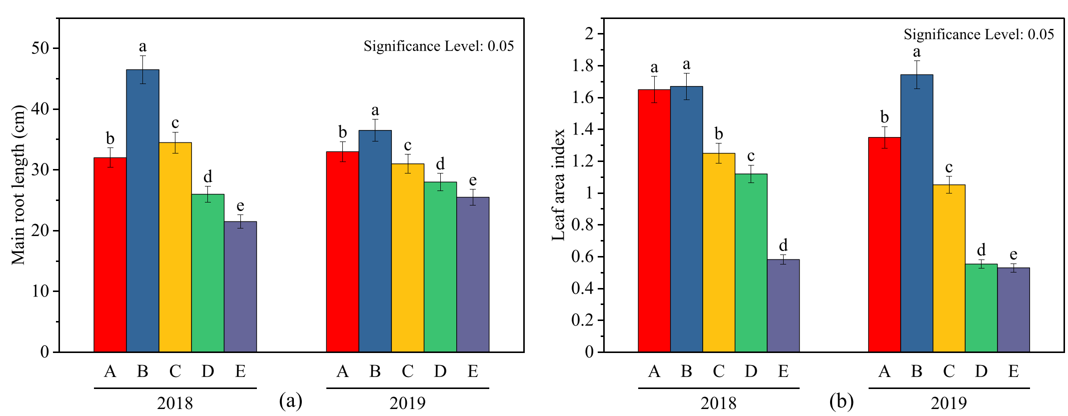

Fig. 11. Comparison of average (± SD) main root length (a) and leaf area index (b) of cotton plants grown in different salinity treatments (A–E) in a field experiment. Lowercase letters indicate significant differences ($P < 0.05$, t − test) between treatments in each year. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, ^{1}2 g L^{-1}.

2018, treatments C, D, and E used 17.5%, 38.1%, and 55.6% less water, respectively, than the plants in treatment B, and they used 25.1%, 43.1%, and 58.7% less water, respectively, in 2019.

4. Discussion

4.1. Effect of water salinity on the soil salinity balance in the root zone area

Saline water irrigation causes salt leaching and the accumulation of salts in the soil. When the leaching process is dominant, irrigation with saline water can be carried out without significant negative effects. When there is significant salt accumulation, saline water irrigation systems need to be supplemented with freshwater. Alternatively, during periods of high evaporation, the irrigation quantity needs to be increased to wash the salt away from the root zone.

A correlation matrix between soil moisture and soil salinity at different soil depths is shown in Fig. 14. The correlation between soil moisture and EC gradually decreased with increasing soil depth. Soil moisture content increases with increasing salinity in the middle and later periods of cotton growth (Liu et al., 2016). Salt that infiltrates the soil via mulched drip irrigation reduces soil water potential, causing salt stress in the cotton root system and affecting soil moisture absorption and utilisation (Chen et al., 2010). In our study, soil EC was strongly affected by the irrigation water salinity levels used in the treatments. The salt content of the surface soil (0–20 cm) is directly affected by irrigation and evaporation, as both leaching and salt accumulation are significant in this zone. When we compared the salt content of the soils at different depths, we found that the surface layer contained the highest amount of salt across all the different salinity treatments. Salt accumulates in the surface layer of soil in response to high surface temperatures, low vegetation coverage, and high evaporation rates. In addition, owing

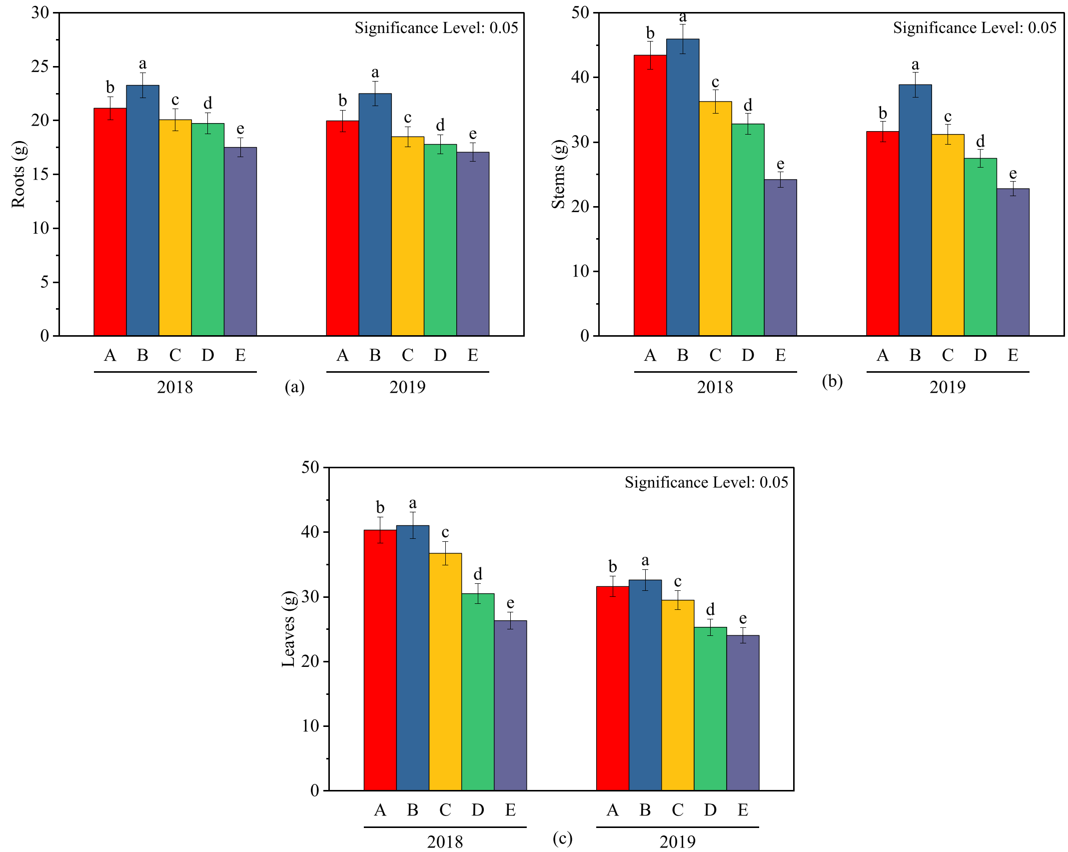

Fig. 12. Average (± SD) dry matter production of roots (a), stems (b), and leaves (c) from plants grown in different salinity treatments in a field experiment. Different lowercase letters indicate significant differences ($P < 0.05$, t−test) between treatments (A–E) in each year. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, ^{1}2 g L^{-1}.

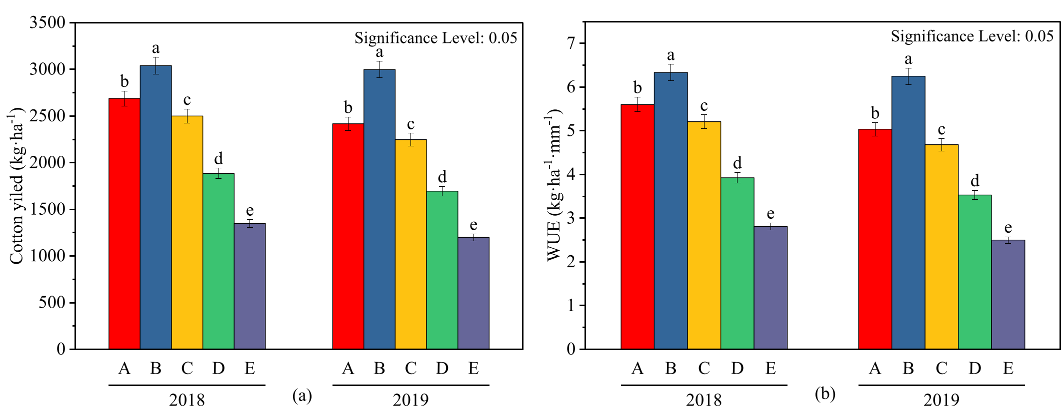

Fig. 13. Average (± SD) yield (a) and water use efficiency (WUE) (b) of cotton grown in different salinity treatments in a field experiment. Different lowercase letters indicate significant differences ($P < 0.05$, t−test) between treatments (A–E) in each year. A, 1 g L^{-1}; B, 3 g L^{-1}; C, 6 g L^{-1}; D, 9 g L^{-1}; and E, ^{1}2 g L^{-1}.

to the concurrent action of water uptake by the cotton roots and capillary force, saline water can be transported from lower soil depths to the surface soil layer (Liu et al., 2012). This can also determine the salt levels in the surface soil layer. This may explain why the salt levels in the surface soil layers were greater than those of the deeper soil layers under all the different salinity treatments in our study. The 20–60 cm zone is where the cotton roots are located and the mulched drip irrigation wetting zone causes salt to leach out of the crop cultivation layer. These factors can have a significant effect on salt distribution in the soil. Under mulched drip irrigation, we found that soil salt levels were generally highest in the periphery (below 60 cm) of the wetted zone. Removal of the salts that have accumulated in this wetting zone 'front' would be required in the long-term to maintain production levels.

Although soil salt levels increased significantly in the first year of treatments with salinity levels from 1 to 3 g L^{-1}, they then stabilised and remained stable during the second year. Similar results were obtained by Li et al. (2016, 2017) in another type of saline soil. Therefore, from the perspective of soil water-salt movement, it is feasible to use water with salt concentrations of 3 g L^{-1} for the irrigation of cotton in arid and semi-arid regions, as it is unlikely to result in secondary salinisation of the soil.

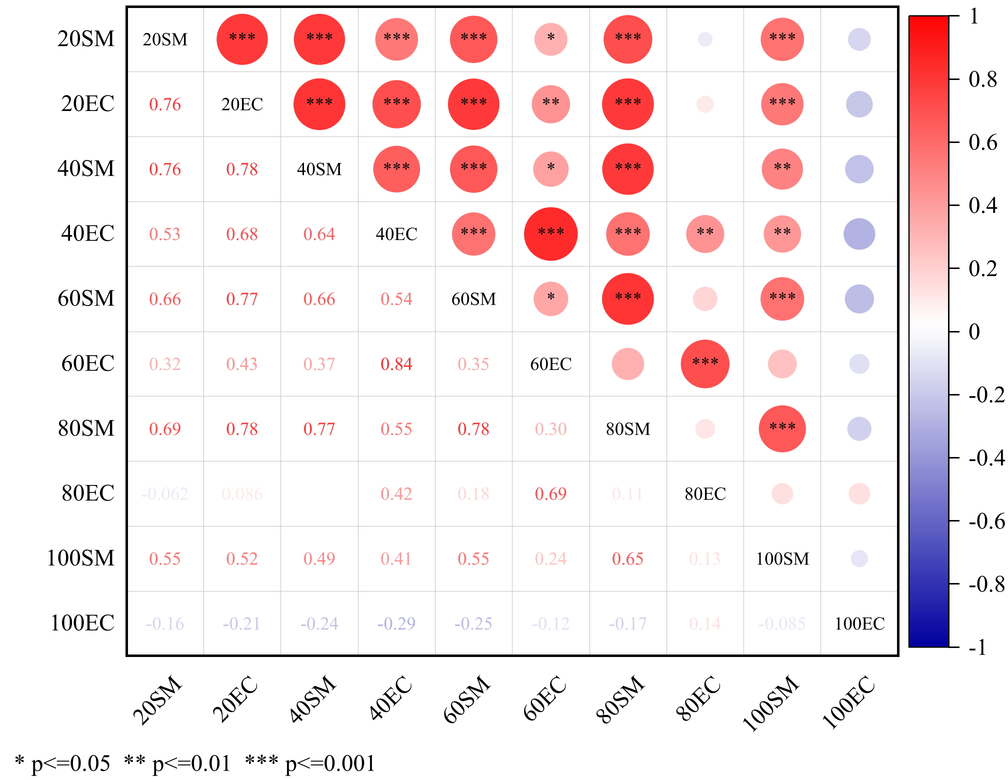

Fig. 14. A correlation matrix comparing soil moisture and soil salinity levels in soil samples taken from different depths under saline water irrigation. EC: electrical conductivity. SM: soil moisture.

4.2. Effect of water salinity on root zone soil hydro-chemical characteristics

Effectively controlling or reducing the accumulation of soil salts, by accelerating the discharge of harmful ions from the soil layer, is an important step towards the safe use of saline water in farmland irrigation. The salts dissolved in irrigation water disperse as ions, each affecting soil conditions and cotton growth in a different way. The effects of the different salinity treatments were mainly related to changes in eight ions and the hydro-chemical characteristics of the soil solution (Zhang et al., 2006). Following saline water irrigation, the composition of the saline ions in the soil changed; harmful ions such as Na^+ and Cl^- increased while K^+ and Ca^{2+} decreased. In this study, the levels of K^++Na^+, Ca^{2+}, SO_4^{2-}, and Cl^- were highest in the 0–20 cm soil layer in each treatment. When the salinity level was less than or equal to 6 g L^{-1}, the surface soil's salt levels were in equilibrium. The SO_4^{2-} content varied widely across the salinity range and it was the most prevalent ion throughout the cotton growth period. The higher the salinity, the higher the Ca^{2+}, K^++Na^+, SO_4^{2-}, and Cl^- content in the soil. Brackish or saline water irrigation causes the salt in the soil to migrate with the irrigation water and salt ions are carried into the soil body (Guo et al., 2005). In our study, salt accumulation increased with increasing irrigation water salinity, i.e. the higher the irrigation water salt content, the greater the salt accumulation and ion content in the soil. Soil ion migration differs depending on the type of salt ion considered. Single-valence ions such as Na^+, Cl^-, K^+, and HCO_3^- are not easily adsorbed onto soil colloids, and these ions tend to move with soil water, accumulating where the water slows. Double-valence ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, and CO_3^{2-} are more easily adsorbed onto soil particles, so they accumulate in the wetted soil body and are evenly distributed through the soil profile. In this study, a small amount of salt accumulation occurred at depths below 60 cm.

Piper diagrams use the milligram-equivalent percentage of the main cations (Na^++K^+, Ca^{2+}, and Mg^{2+}) and anions (Cl^-, SO_4^{2-}, and HCO_3^-+CO_3^{2-}) in each litre of water to illustrate the chemical characteristics of the hydrological system in the soil (Ray and Mukherjee, 2008). Combined with the hydrogeological conditions of an area, they can be used to analyse the evolution of its groundwater chemistry (Chadha, 1999). In our study, the main cation type at the outset was Ca^{2+}, at a milligram-equivalent percentage of 50–80%, and the main anion types were SO_4^{2-}, Cl^-, and HCO_3^-, at 80–100%. At high irrigation salinities, the soil hydro-chemical characteristics in the root zone changed from SO_4^{2-} and HCO_3^- to Cl^-, and fromCa^{2+} to Mg^{2+} and K^+.

4.3. Effect of water salinity on physiological and biochemical processes in cotton

Salts had both general and specific effects on cotton growth that directly affected crop yields. Although cotton is relatively salt-tolerant, high soil salinity levels affect its growth and development (Ahmed et al., 2012). Saline water irrigation reduces the water potential of the soil solution, thus causing soil-root-leaf osmotic stress which causes water absorption problems in the plant roots (Fig. 15). These effects induce a series of physiological and biochemical changes in cotton under salt stress (Niu et al., 2010), including partial stomatal closure; and a reductions in stomatal conductance and the transpiration rate of leaves, affecting growth, photosynthesis, and CO_2 balance. These changes ultimately affect dry matter accumulation and yield (Koyro et al., 2008). Canopy photosynthesis can provide 90–95% of total dry matter production (Ludlow, 1985). We found that saltwater irrigation can cause salt stress, which can reduce the Pn, Tr, and Gs of cotton. Analysing the causes showed that salt stress caused by saltwater irrigation increased the osmotic potential of the soil solution, reduced the effectiveness of soil water use, damaged the cytoplasmic membranes of cotton roots, increased the water potential gradient of cotton leaves, caused cellular osmotic stress, hindered the absorption of nutrients and water, decreased stomatal opening on cotton leaf surfaces, and decreased the rate of CO_2 entering the mesophyll cells. This all leads to a decrease in

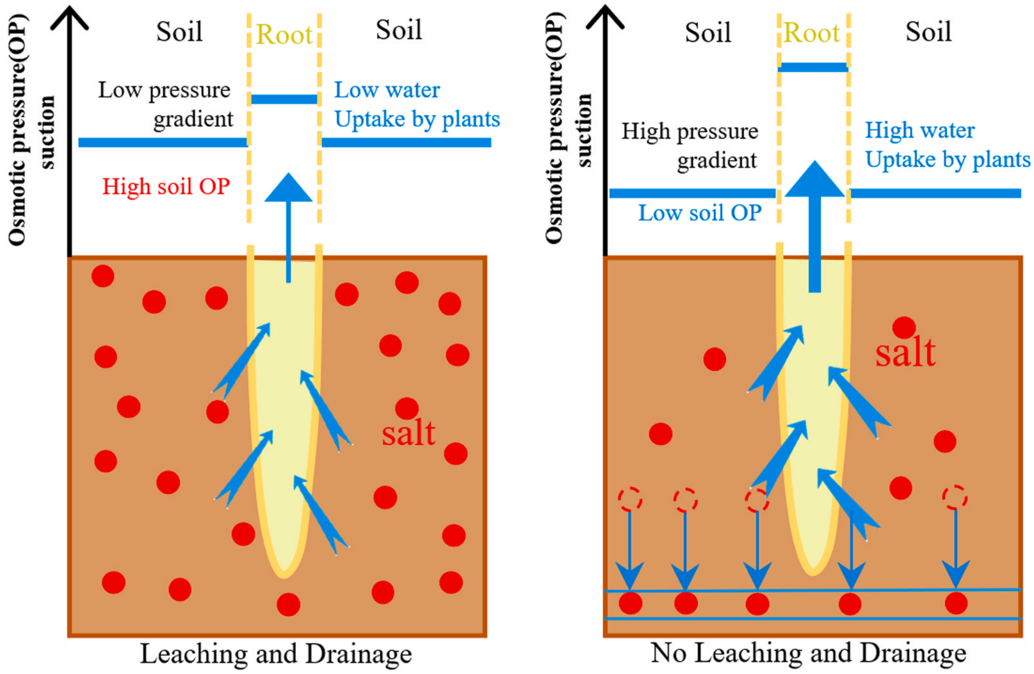

Fig. 15. Water uptake by plants in saline soils with or without a leaching and drainage system. In a saline soil without a leaching and drainage system, the osmotic pressure associated with the salt reduces the pressure gradient between the soil and the root, reducing the flow of water into the root. This reduces the water available to the plant for growth and yield.

photosynthesis. At higher irrigation water salinity levels, the Ci of the cotton increased. Moreover, salt stress also leads to leaf stomatal contraction, which limits the absorption of atmospheric CO_2 by the leaves and leads to insufficient photosynthesis. This may have resulted in the observed reduction in cotton yield. Analysing the causes showed that the accumulated salt ions absorbed from the soil by the cotton plants, destruction of chloroplast structures, and the decrease in mesophyll cells photosynthetic activity led to higher Ci values. This indicates that the Pn, Tr, and Gs of cotton are limited by Ci.

Our results showed that the Fm, Fv/Fo, and Fv/Fm of cotton decreased with increasing irrigation water salinity. With an increase in salt stress, the concentrations of reactive oxygen species, such as superoxide, hydroxyl groups (•OH), hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), and other non-free radicals, increase. This causes membrane lipid peroxidation, protein oxidation, and damage to lipids, proteins, and nucleic acid, which all contribute to abnormal metabolism functioning. This, in turn, results in reductions in the initial chlorophyll fluorescence, maximum photochemical efficiency, photochemical quenching coefficient, apparent quantum efficiency, light compensation and saturation points, electron transfer rate, maximum net photosynthetic rate, and dark respiration rate. In summary, it is likely that the salt stress in our study led to a reduction in cotton photosynthesis when the dark reaction of the photosynthetic electron transport chain was impaired, photosynthesis between photosystem II and I was undermined, and CO_2 assimilation was limited.

4.4. *Effect of water salinity on cotton growth processes*

It has been found that 85% of the cotton root system is distributed in the 30–50 cm soil layer under mulched drip irrigation (Yang et al., 2017b). Cotton root growth is extremely sensitive to variations in soil conditions. The presence of salt in the root zone can have a major effect on growth. This is the largest problem facing cotton growers who depend on irrigation. Cotton root systems grow better in irrigation systems when there is a high soil moisture content and low soil salinity. Cotton roots first absorb soil water through their deep roots, which have a high water potential. Therefore, most of the water initially taken up by the roots is from a less saline soil depth. However, as more water is removed, the total water stress increases to a level equal to that in the lower depths. After this, water is also absorbed from the shallower, more saline, soil layers, and the effect of salinity on cotton growth is magnified. In this study, the main root length and dry matter production were highest in plants grown in the 3 g L^{-1} salinity treatment. A good root system increases water and nutrient uptake and consequently improves cotton yield and WP (Feng et al., 2017).

The leaf is an important vegetative organ in cotton, as in many plants, as it is the key site of photosynthesis (Landivar et al., 1983). In our study, the effect of salt stress on cotton growth was indicated by changes in leaf growth. LAI values measured over time reflected changes in leaf area within the experimental plant populations. LAI is also indicative in terms of several important parameters, including photosynthesis, transpiration, and biomass formation (Sinclair and Horie, 1989). The amount of salt in the soil affects plant biomass and the distribution of the root system. With increasing soil salt levels, the growth of cotton roots becomes seriously inhibited, and the yield is reduced (Miura and Tada, 2014). Our results show that a salinity level of more than 6 g L^{-1} inhibited the expansion of cotton leaf cover, leading to a decrease in the LAI and leaf dry mass. Higher salinities caused slower growth and lower roots, stems, and leaf qualities, as well as lower LAIs and yields.

The accumulation of cotton biomass is the basis for obtaining high-yield and high-quality cotton. Cotton has a high salt tolerance, and soil salt may increase the dry matter accumulation of cotton within a range suitable for cotton growth. With increasing irrigation frequency, we found that the soil salt content also gradually increased. The treatment which induced only slight salt stress in the cotton plants had little effect on dry matter accumulation per cotton plant, whereas the severe treatment strongly inhibited it. Optimal levels of saline water irrigation are favourable to the development of cotton root systems under mulched drip irrigation, as it causes the dry matter accumulation and WP to increase. Water salinity levels of 3 g L^{-1} may significantly increase the accumulation of dry matter in cotton and promote the transfer of nutrients from the vegetative organs to the reproductive organs. We found that, when the water salinity level was greater than or equal to 6 g L^{-1}, the accumulation of dry matter greatly inhibited nutrient transfer. The question of how to compensate for this effect to create optimal conditions for crop roots to absorb water when the soil osmotic potential has been reduced by saline water irrigation remains unanswered and requires significant future research (Fig. 15).

4.5. Effect of water salinity on cotton yield and WP

Generally, the water potential of soil of any given texture depends on its moisture and salt levels. At any fixed drip irrigation input rate, the more saline the irrigation water, the more salt ions are carried into the soil body, and the lower the soil water potential and osmotic effects. This inhibits plant water absorption and causes a ‘chemical drought’ where crops wither owing to water shortage, despite the soil remaining moist (Fig. 15) (Rengasamy, 2010). In contrast, water salinity has a greater effect on water consumption by cotton and WP strongly affects total water consumption (Sinclair et al., 1984). Our research has shown that WP was significantly compromised when the water salinity was greater than 9 g L^{-1}. However, we also found that the WP improved as the salinity levels increased from 1 to 6 g L^{-1}. The main reasons for this were that cotton stops growing during the bolling stage, and that the water consumption of cotton mainly depends on the evaporation intensity at ground level and the total amount of water contained in the soil. When mulched drip irrigation with highly saline water is used, there are more salts in the soil, and it has a lower water potential, which makes it difficult for the cotton roots to absorb water.

Saline water always contains high concentration of trace elements (Zn, B), which may be conducive to cotton growth because the cooperation and antagonism between trace elements and salt can lessen salt damage (Chen et al., 2017, 2018). Cotton yield was significantly influenced by the salinity levels of the irrigation water. In addition, the high concentrations of salt in the irrigation water inhibited cotton growth. The long-term use of brackish and saline water irrigation causes a dramatic decrease in cotton yield. When irrigated with saline water, the cotton yields in treatments C, D, and E were substaintially lower than those in treatments A and B. This indicates that low concentrations of saline water may reduce salt accumulation, thereby reducing salt stress in the root zone.

4.6. Utilisation of saline water for agricultural irrigation in semi-arid and arid regions

Ocean covers approximately 71% of the globe. Saline water constitutes 97.5% of all water resources with only 2.5% being freshwater. Agricultural practices consume a large portion of these freshwater resources and global agricultural irrigation is still dependent on freshwater while most brackish and saline water resources have not been used for irrigation. In China, 5.569 billion m3 of 1–3 g L^{-1} saline water is exploited every year. Moreover, approximately 151 million m^3 of 3–5 g L^{-1} saline water is also exploited. The sustainable development and utilisation of saline water resources are imperative, as this would not only increase agricultural water resources, but also alleviate the water shortage crises in semi-arid and arid areas, such as in Xinjiang, in North-western China.

Salinity management is a significant step towards the safe utilisation of saline water irrigation, and it involves the reduction of the salt content in the soil to levels that are not harmful to cotton. This results in more water being added to the soil than is needed for cotton growth. This excess water infiltrates the soil and percolates through the root zone soil layer. During percolation, it takes a portion of the salt with it and leaches this salt into the deeper soil layers. Interestingly, saline water also leaches salt out of the root zone. However, the excess irrigation water that causes leaching needs to be eliminated from the root zone and the deeper soil layer. If it is not eliminated, it can lead to a rise in the groundwater, which may transport the salt back into the root zone through capillary forces. Therefore, water loss and groundwater levels must be rigorously monitored and controlled to permit adequate root development. To that end, soil salinity management under long-term saline water irrigation must enable leaching and sub-surface drainage, to allow for the removal of salts and the maintenance of an optimal salt balance (Fig. 15). These processes are essential for the prevention and reduction of salinisation.

Certain irrigation water salinity levels may induce a salt inhibition effect. The effect of irrigation volumes, times, and periods on soil conditions and cotton growth, especially during periods when crops are sensitive to salt levels, needs further study. To date, most research has been based on indoor simulation experiments and short-term field experiments. However, the effects of brackish and saline water on soil and crops are long-term. It is therefore essential to establish long-term field experiments that evaluate the effects of saline water irrigation on soil water-salt movement dynamics, cotton physiology, and crop yield. Further study is needed to evaluate the sustainability of saline water irrigation and provide management principles and practices for the safe utilisation of saline water irrigation in semi-arid and arid regions.

5. Conclusions

Ensuring the effective exploitation and utilisation of saline water resources, as well as establishing normative salinity water irrigation schedules, are pressing problems in semi-arid and arid regions. Based on the results obtained from a two-year field experiment performed in 2018 and 2019, our main conclusions are as follows: using the optimal water salinity level in mulched drip irrigation can accelerate photosynthesis, thereby improving cotton yield. Irrigation water salinity levels above or below this optimum level will retard photosynthesis and reduce cotton yield. The transpiration rates, net photosynthetic rates, main root lengths, and cotton yields of the plants grown under irrigation water salinity levels of 3 g L^{-1} were the highest among our treatments. This salinity level, therefore, is the most suitable for mulched drip irrigation; it ensures that the water demand for cotton growth is met and does not cause salt stress that affects cotton physiology or growth. WP decreased with increasing irrigation water salinity levels above 3 g L^{-1}. The maximum WP values were observed at salinity level of 3 g L^{-1}. At salinities of 1–6 g L^{-1}, the WP values were significantly higher than those of plants grown under higher salinity conditions, while the cotton yields remained unchanged. When cotton was irrigated with saline water under mulched drip irrigation in a natural environment, a salinity level of 3 g L^{-1} was found to benefit cotton growth and improve WP and did not result in secondary soil salinisation. Under long-term saline water irrigation and water-salt stress, the mechanisms by which water and salt move through the cotton root zone and their influence on cotton yield and quality need further study to improve cotton production efficiency and control soil salinisation.

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CRediT authorship contribution statement

Guang Yang: Conceptualization, Validation, Original draft preparation, Data curation, Visualization. **Futian Ren:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Yongli Gao:** Conceptualization. **Xinlin He:** Methodology, Validation, Supervision, Project administration, Funding acquisition. **Zelin Wang:** Software, Resources. **Lijun Tian:** Formal analysis. **Saihua Liu:**

Investigation. **Fadong Li:** Supervision. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.106859.

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