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Effects of water salinity and N application rate on water- and N-use efficiency of cotton under drip irrigation

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Abstract: In arid and semi-arid regions, freshwater scarcity and high water salinity are serious and chronic problems for crop production and sustainable agriculture development. We conducted a field experiment to evaluate the effect of irrigation water salinity and nitrogen (N) application rate on soil salinity and cotton yield under drip irrigation during the 2011 and 2012 growing seasons. The experimental design was a 3×4 factorial with three irrigation water salinity levels (0.35, 4.61 and 8.04 dS/m) and four N application rates (0, 240, 360 and 480 kg N/hm^2). Results showed that soil water content increased as the salinity of the irrigation water increased, but decreased as the N application rate increased. Soil salinity increased as the salinity of the irrigation water increased. Specifically, soil salinity measured in 1:5 soil:water extracts was 218% higher in the 4.61 dS/m treatment and 347% higher in the 8.04 dS/m treatment than in the 0.35 dS/m treatment. Nitrogen fertilizer application had relatively little effect on soil salinity, increasing salinity by only 3%–9% compared with the unfertilized treatment. Cotton biomass, cotton yield and evapotranspiration (ET) decreased significantly in both years as the salinity of irrigation water increased, and increased as the N application rate increased regardless of irrigation water salinity; however, the positive effects of N application were reduced when the salinity of the irrigation water was 8.04 dS/m. Water use efficiency (WUE) was significantly higher by 11% in the 0.35 dS/m treatment than in the 8.04 dS/m treatment. There was no significant difference in WUE between the 0.35 dS/m treatment and the 4.61 dS/m treatment. The WUE was also significantly affected by the N application rate. The WUE was highest in the 480 kg N/hm^2 treatment, being 31% higher than that in the 0 kg N/hm^2 treatment and 12% higher than that in the 240 kg N/hm^2 treatment. There was no significant difference between the 360 and 480 kg N/hm^2 treatments. The N use efficiency (NUE) was significantly lower in the 8.04 dS/m treatment than in either the 4.61 dS/m or the 0.35 dS/m treatment. There was no significant difference in NUE between the latter two treatments. These results suggest that irrigation water with salinity <4.61 dS/m does not have an obvious negative effect on cotton production, WUE or NUE under the experimental conditions. Application of N fertilizer (0–360 kg N/hm^2) could alleviate salt damage, promote cotton growth, and increase both cotton yield and water use efficiency.

Keywords: saline water; nitrogen; soil salinity; cotton; water use efficiency; nitrogen use efficiency

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With increasing human population and rapid economic growth, the shortage of fresh water has become a fundamental and chronic problem for sustainable agriculture development in arid regions. Meanwhile, the quality of irrigation water has also deteriorated (Jiang et al., 2012). Irrigation with saline water has become inevitable in arid and semi-arid regions (Assouline et al., 2006; Letey et al., 2007). However, the use of saline or brackish water increases the risk of soil salinization due to salt accumulation in the root zone (Pereira et al., 2002). When saline water is used for irrigation, increases in the amount of water and in

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the frequency of irrigation are both needed to prevent salt accumulation (Corwin et al., 2007). Under these conditions, soluble nutrients in soil such as nitrates can leach from the root zones and migrate to groundwater. This may reduce fertilizer use efficiency and increase the risk of groundwater contamination (Dudley et al., 2008). Therefore, the goal for the safe and efficient use of saline or brackish water for agriculture irrigation is to maximize water and nutrient use efficiency and crop production, and to minimize salt accumulation in the root zone and groundwater pollution. This requires the selection of the most appropriate irrigation system, salt tolerant crops and a suitable water management strategy (Malash et al., 2008).

Drip irrigation has gained widespread popularity as an efficient irrigation method. In drip irrigation systems, the application rates of water and nutrients are controlled to meet the requirements of the crop at each growth stage. This leads to high water and nutrient use efficiency (Assouline et al., 2006; Hou et al., 2007). In many arid regions, water scarcity is increasing and water quality is deteriorating. The scarcity of fresh water in these regions makes brackish water and saline water a valuable alternative water source for irrigation (Wang et al., 2008). Cotton is grown widely in Xinjiang, and the planting area has expanding rapidly since the introduction of drip irrigation, plastic mulching and high planting density in the late 1990s (Wang et al., 2004). Drip irrigation is the most efficient irrigation method for applying saline water to crops. One reason is that drip irrigation reduces the salinity hazard to plants by maintaining high soil water potential within the root zone, thus damping the osmotic effects exerted by saline water irrigation and maximizing the beneficial use of available water for crop growth (Bucks et al., 1982; Oster, 1994; Batchelor et al., 1996; Ayars et al., 1999; Wang et al., 2002).

Nitrogen is the main nutrient limiting agricultural production in arid and semiarid regions. Crops require more N than other nutrients. Researchers have given increased attention to N fertilizer management in salt-affected fields in recent years. Proper N fertilizer management is necessary in all soils, but it is particularly important in saline soils where N can reduce the negative influence of salinity on crop growth, development and yield (Villa-Castorena et al., 2003; Esmaili et al., 2008; Hou et al., 2009). Ding et al. (2010) reported that NO_3^--N had both nutritional and osmotic roles in saline conditions. Crop dry matter and yield both decreased as salinity increased but they increased as the N application rate increased (Homaee et al., 2002). However, Chen et al. (2010a) found that cotton growth was significantly affected by interaction between soil salinity and N. When soil salinity was low, an increase in the N application rate alleviated adverse effects caused by salinity. With moderate soil salinity, proper use of N fertilizer was necessary, but over-fertilization did not benefit N uptake. At high soil salinity, salt was the dominant factor governing cotton growth and N uptake. Zhang et al. (2012) showed that maximum lint yields and N use efficiency could be achieved either with moderate N application rates under moderate salinity or with low N application rates under high salinity. Hou et al. (2010) reported that increasing the N application rate significantly promoted the growth and N uptake of cotton irrigated with either fresh or brackish water. However, increased N application had little effect on cotton irrigated with saline water. The main reason was that saline water inhibited N uptake. Regarding evapotranspiration (ET), Zhu et al. (2011) observed that saline water irrigation increased the accumulation of salt in the root zone, resulting in a reduction in ET, but an increase in water deep percolation and N leaching.

Proper N fertilizer and water management is essential in saline water-irrigated soils to sustain crop yield and to minimize the degradation of soil and the deterioration of groundwater. However, no information is available on the interactive effects of irrigation water salinity and N application rate on soil salinity and cotton growth under drip irrigation conditions. The objectives of this work were (1) to determine the influence of different water salinity levels and N fertilization rates on soil salinity, soil water content and cotton yield, and (2) to assess water use efficiency (WUE) and N use efficiency (NUE) in order to understand the interactive effects of N and water salinity on cotton growth.

1 Materials and methods

1.1 Study area

The field experiment was conducted at an agricultural experimental station at Shihezi University (44°18'N, 86°02'E), Xinjiang Uygur autonomous region, China, during the 2011 and 2012 growing seasons. The region is classified as a temperate arid zone with a continental climate. Cotton is usually planted in late-April and harvested in late-September. Rainfall during the cotton growing period was 136 mm in 2011 and 82 mm in 2012. Annual potential evaporation is about 1,660 mm. The groundwater table is about 6 m below the soil surface.

The soil in the study area is classified as an alluvial, gray desert soil. Physical and chemical properties of the soil (0–0.2 m depth) were as follows: bulk density, 1.33g/cm^3; pH, 7.48; electrical conductivity (EC) of 1:5 soil:water extract, 0.13 dS/m; organic matter, 16.84 g/kg; total N, 1.08 g/kg; available P, 25.86 mg/kg; and available K, 253 mg/kg. The cotton cultivar used in this study was *Gossypium hirsutum* L. cv Xinluzao 36.

1.2 Experimental design

The irrigation experiment using different saline water (EC of water: 0.35, 4.61 and 8.04 dS/m) was conducted at the study area for two years (2009–2010) before the start of this experiment. The irrigation rate, as well as the fertilizer application rate, was the same in all plots for both years. At the end of the experiment, soil salinity was measured at five depths in each plot. The data are shown in Table 1.

Table 1 Soil salinity at five depths in the soil profile under three water salinity treatments prior to the beginning of our experiment in 2011

Water salinity (EC, dS/m)	Soil salinity ($EC_{1:5}$, dS/m)				
	0–0.2	0.2–0.4	0.4–0.6 (m)	0.6–0.8	0.8–1.0
0.35	0.16	0.19	0.23	0.24	0.21
4.61	0.35	0.55	0.58	0.59	0.57
8.04	0.53	0.75	0.81	0.79	0.69

In this study, we used a 3×4 factorial design with three salinity levels of irrigation water and four N application rates. The ECs of the irrigation water were the same as in the previous experiment: 0.35, 4.61 and 8.04 dS/m. These treatments will be referred to as fresh water (FW), brackish water (BW) and saline water (SW), respectively throughout the rest of the paper. Both the brackish and the saline irrigation water were prepared by adding equivalent amounts of NaCl and $CaCl_2$ to fresh water (van Hoorn et al., 2001). Table 2 shows the chemical composition of the irrigation water. The N application rates were 0, 240, 360 and 480 kg N/hm^2, representing no (N0), low (N240), medium (N360) and high (N480) fertilization rates, respectively. The medium fertilization rate is commonly used by local farmers.

Our experiment, as well as the previous one, used a completely randomized block design with three replications for each treatment. The research area was split into 36 plots, each with an area of 30 m^2. In each plot, there were two 1.2 m×16 m beds, with a 0.6-m separation distance (Fig. 1). Each bed had four plant rows and the soil surface was covered with plastic film. Two irrigation drip lines were installed under the plastic film. The cotton plants were sown at 0.1-m intervals within each row to obtain a population of 222,000 plants/hm^2. One metal cylinder (0.4-m internal diameter) was installed to a depth of 1 m in each plot to monitor leaching prior to the beginning of the first experiment in 2009 (Fig. 1). Drainage tubes at the bottom of the columns were used to collect the leachate.

Cotton was planted on 25 April 2011 and 15 April 2012. The growing seasons were from April to September. Water was applied by drip irrigation at a rate of 2.7 L/h. The emitters were 0.4 m apart. All plots were drip-irrigated with 30-mm freshwater at sowing to improve germination and seedling establishment. During the 2011 cotton growing season, 450 mm of irrigation water was applied. The 2012 growing season was drier, so we applied 510 mm of irrigation water. The plots were irrigated nine times between June and August. The irrigation interval was 7–10 days based on the common field practices used by local farmers for fresh water-irrigated soils. The plots were all irrigated on the same dates and with equal watering depths. The amount of water applied was measured using a flow meter. The N fertilizer was applied through the drip irrigation system during the cotton growing season. In keeping with local practices, urea was used as the N source. The N fertilizer was applied in six equal amounts 64, 71, 78, 85, 92 and 99 days after planting (DAP) in 2011 and 70, 77, 84, 91, 98 and 105 DAP in 2012. The urea fertilizer solution was stored in a 15-L plastic container and

Table 2 Chemical characteristics of the three types of irrigation water in our study

Water salinity (EC, dS/m)	pH	SAR	Ion concentration (mEq/L)						
			K^+	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}
0.35	7.52	0.16	0.33	0.22	2.44	1.18	0.98	2.46	0.73
4.61	7.18	6.74	0.33	25.52	27.50	1.18	1.07	52.57	0.83
8.04	7.09	8.91	0.33	43.04	45.50	1.18	1.15	88.00	0.83

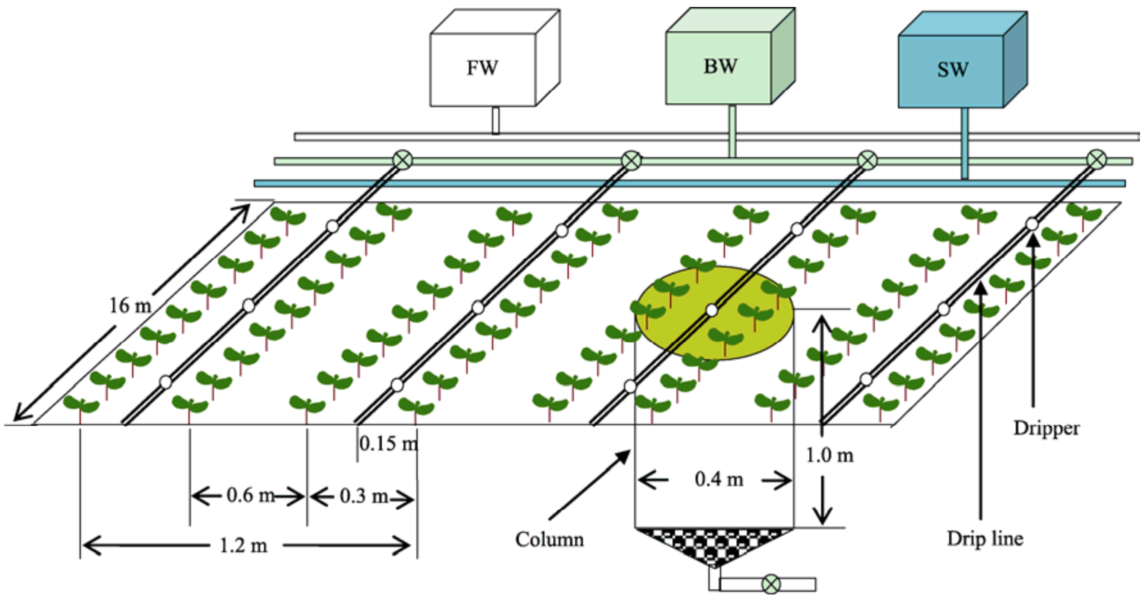


Fig. 1 Layout of the experimental plot and distribution of the instruments. The symbols FW, BW and SW represent irrigation water salinity (EC) of 0.35, 4.61 and 8.04 dS/m, respectively.

pumped into the irrigation system. All plots were fertilized with 105-kg P_2O_5/hm^2 and 60-kg K_2O/hm^2 before sowing each year.

1.3 Sampling and measurement methods

Soil moisture and soil salinity were both measured periodically at different depths in the soil profile before and after irrigation. Soil samples were taken from six randomly chosen points in each plot at depths of 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1.0 m. Soil cores from the same plot and depth were pooled and mixed before the measuring of soil salinity. The gravimetric water content of the soil was measured by drying the soil at 105°C for 24 h. Soil salinity was measured as the electrical conductivity of 1:5 soil:water extracts ($EC_{1:5}$) with a DDS-308A conductivity meter (Shanghai Precision & Scientific Instrument Inc., Shanghai, China).

At harvest, the cotton plants were cut at the soil surface and partitioned into leaves, stems and bolls. Each plant component was washed with distilled water and then dried in an oven at 70°C for 48 h. The dry samples were weighed, ground to pass a 1-mm sieve, and then digested with concentrated H_2SO_4-H_2O_2 before elemental analysis. The N concentration was measured using an Auto-Kjeldal Unit (B-339, Buchi Labortechnik AG, Switzerland). Cotton yields were measured in the field by weighing the seed cotton.

Plant N uptake was calculated by multiplying the N content of each plant component (leaf, stem and boll) by its corresponding dry mass. Total N uptake was calculated by summing the N content of all the plant components. The NUE of different N application rates under the same water salinity level was evaluated by apparent N recovery (ANR) according to Good et al. (2004) and Chen et al. (2010a).

$$\text{ANR (\%)}=(N_F\ \text{uptake}-N_C\ \text{uptake})/N_F\times100. \quad (1)$$

Where N_F uptake is the total N uptake of cotton plants (kg/hm^2) receiving N fertilizer; N_C uptake is the total N uptake of non-fertilized cotton plants (kg/hm^2); and N_F is the total amount of N fertilizer applied (kg/hm^2).

Irrigation water use efficiency (IWUE, kg/m^3) was calculated on the basis of seed cotton yield as follows

(Ibragimov et al., 2007):

$$IWUE=(Y–Y_D)/I. \quad (2)$$

Where Y is the seed cotton yield under irrigated conditions (kg/hm^2); Y_D is the seed cotton yield under non-irrigated conditions (kg/hm^2); and I is the amount of irrigation water applied (mm). Rainfall amounts were so low in both 2011 and 2012 that there would have been no cotton yield without irrigation (Ibragimov et al., 2007).

Water use efficiency (WUE, kg/m^3) was calculated as the ratio of crop production (seed cotton yield, kg/hm^2) to crop evapotranspiration (ET, mm) (Oweis et al., 2000). Crop evapotranspiration during the growing season was determined from sowing to harvest for each plot using the following soil-water balance equation (Oweis et al., 2000):

$$ET=I+P+\Delta S–D. \quad (3)$$

Where I is the amount of irrigation water applied (mm); P is the amount of precipitation (mm); ΔS is the change in soil water storage (mm); and D is the downward drainage below the 1.0-m soil depth (mm). No surface runoff occurred at any time during the growing seasons.

1.4 Data analyses

The experimental data were analyzed using SPSS version 11.5 (SPSS Inc., Chicago, IL) with two-way ANOVA at a significance level of 0.05. The salinity of the irrigation water and the N application rate were treated as independent variables. A Duncan multiple range test was carried out to determine if there were significant differences between individual treatments at $P<0.05$.

2 Results and discussion

2.1 Soil water content

Soil water contents were measured to the 1.0 m depth 48 h after drip irrigation. The data are presented in Fig. 2. The soil water contents were higher in the BW and SW treatments than in the FW treatment, especially in 2012 (Fig. 2b). The no-fertilizer treatment (N0) had a higher water content than either the medium (N360) or high (N480) fertilizer treatment. Moisture in the soil profile under different treatments showed a similar pattern. Soil water content was highest in the 0.6–0.8 m depth and lowest in the 0–0.2 m depth. Comparing

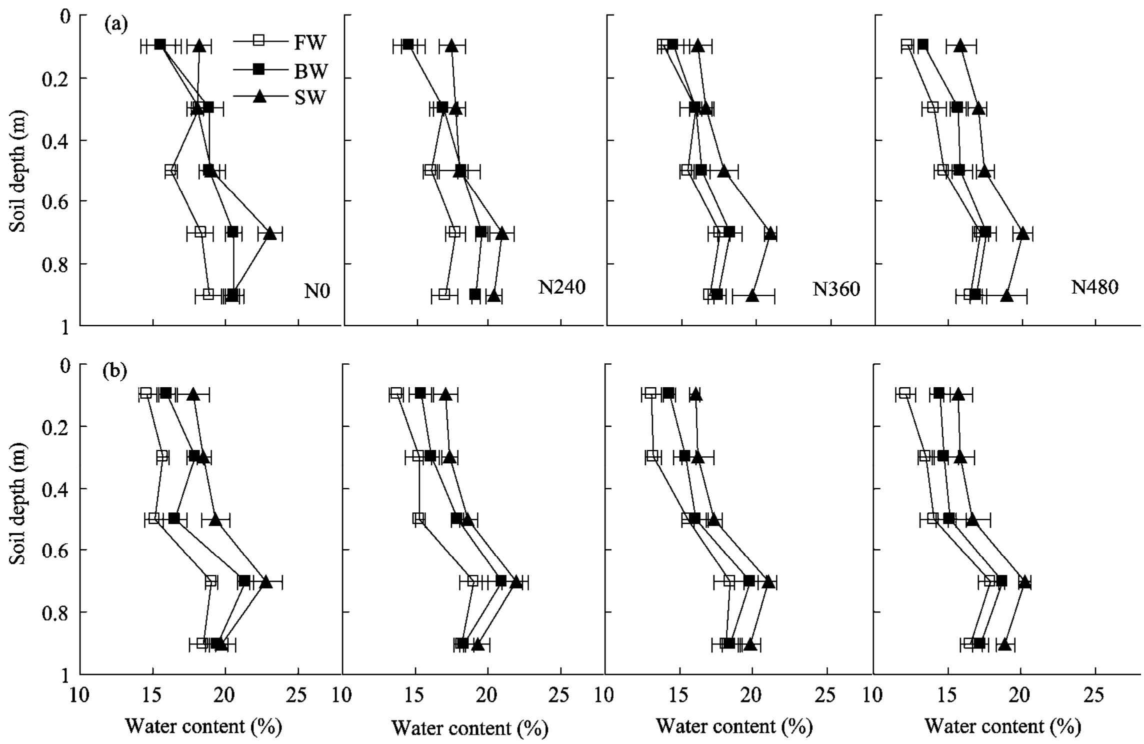


Fig. 2 Soil water content distribution in the 0–1.0 m profile 48 h after the sixth irrigation at 94 DAP in 2011(a) and at 100 DAP in 2012 (b). Error bars represent SDs. The symbols N0, N240, N360 and N480 represent the 0, 240, 360 and 480 kg N/hm^2 treatments, respectively.

the FW, BW and SW treatments, the greatest differences in soil water content were observed in the surface layer (0–0.2 m). The soil water content in the 0.8–1.0 m depth was nearly the same among all treatments (data not shown).

Temporal changes in the average water content in the 0–1.0 m soil profile under different irrigation water salinity and N application rate treatments during the cotton growing seasons in 2011 and 2012 are presented in Fig. 3. Soil water contents before the first irrigation and after the last irrigation were higher in 2011 than in 2012 due to relatively low precipitation in 2012. Average water content in the soil profile was significantly affected by water salinity. The average soil water content in the FW treatment was lower than that in the BW or SW treatment in both 2011 and 2012. At cotton harvest (136 DAP in 2011 and 145 DAP in 2012), the average soil water content was highest in the SW treatment, being 10% higher than that in the BW treatment and 38% higher than that in the FW treatment. This suggests that both brackish water irrigation and saline water irrigation can increase soil water content in the root zone, mainly because of reduced evapotranspiration of high-salinity water (Romero-Aranda et al., 2001; Malash et al., 2008).

The average soil water content in the 0–1.0 m soil

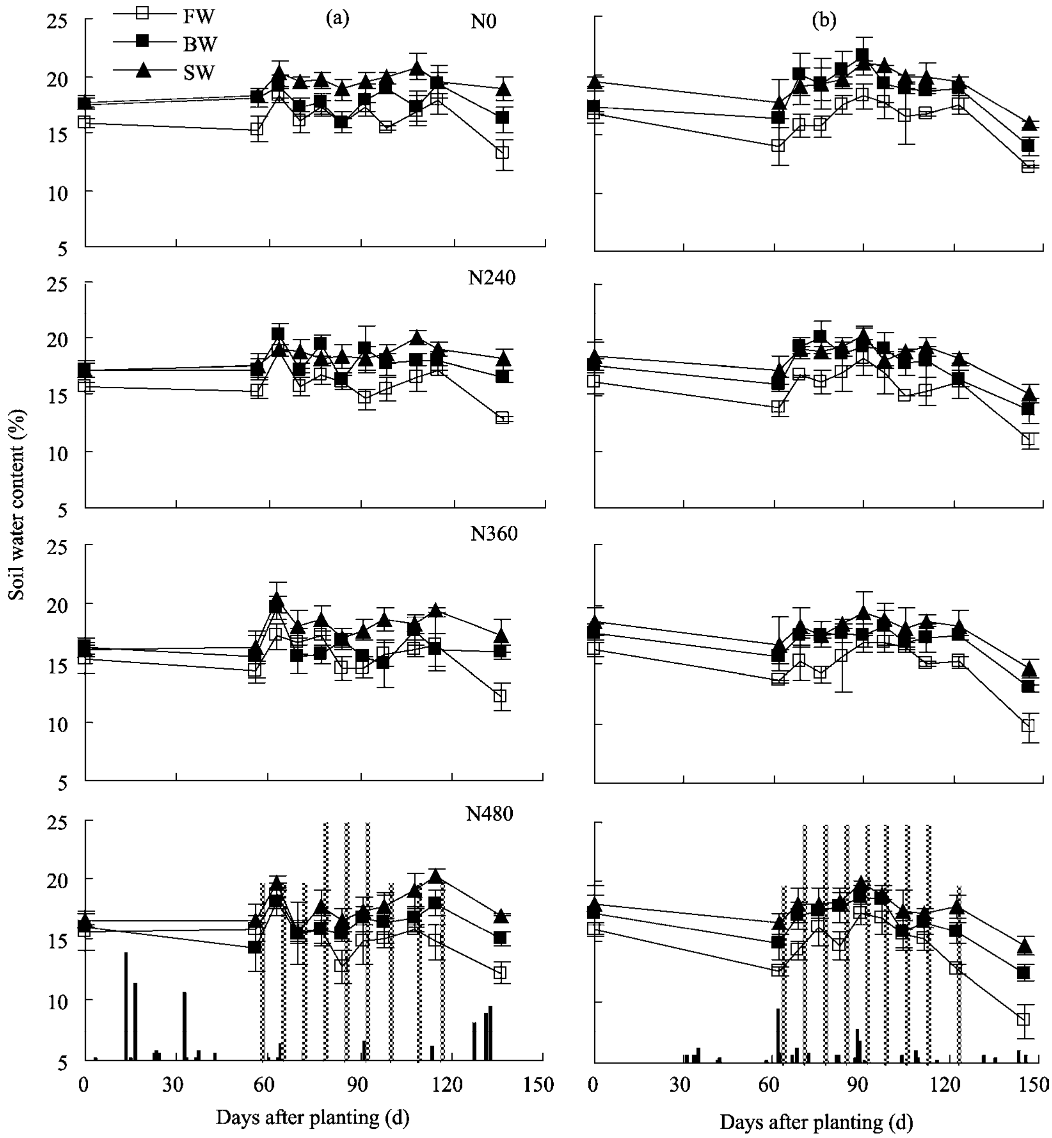


Fig. 3 Average soil water contents in the 0–1.0 m soil profile under different N application rates in 2011 (a) and 2012 (b). Error bars represent SDs. Vertical dashed lines indicate the dates of irrigation. The irrigation amounts were 45 or 60 mm. Solid lines indicate the dates of rainfall. Measurements were taken one day before irrigation.

profile was also affected by N application rate. Overall, the average soil water content decreased in the order of N0>N240>N360>N480. At cotton harvest in 2011 (136 DAP), the N0 treatment had the highest soil water content (16.06%, w/w), 8% higher than that in the N360 treatment (14.93%, w/w) and 11% higher than that in the N480 treatment (14.47%, w/w). There was no significant difference in average soil water content between the N240 (15.85%, w/w) and the N0 treatments (16.06%, w/w). The N application rate had a similar effect on soil water content in 2012 as in 2011. The results suggest that increased N application rate tends to increase water uptake and transpiration, which in turn promotes plant growth. Zhang et al. (2012) reported that N fertilization was beneficial to biological yield formation of the cotton regardless of salinity.

2.2 Soil salinity

The effects of irrigation water salinity and N application rate on soil salinity are shown in Fig. 4. As previously mentioned, an experiment about saline water irrigation had been conducted on the same plots during the 2009 and 2010 growing seasons. The salinity of the irrigation water in the first study was the same as in our experiment (i.e. EC: 0.35, 4.61 and 8.04 dS/m). Soil salinity was already significantly different among the treatments at the start of our experiment in 2011. Soil salinity increased gradually in the BW (4.61 dS/m) and SW (8.04 dS/m) treatments between 2011 and 2012. In contrast, there was little change in soil salinity in the FW treatment (0.35 dS/m).

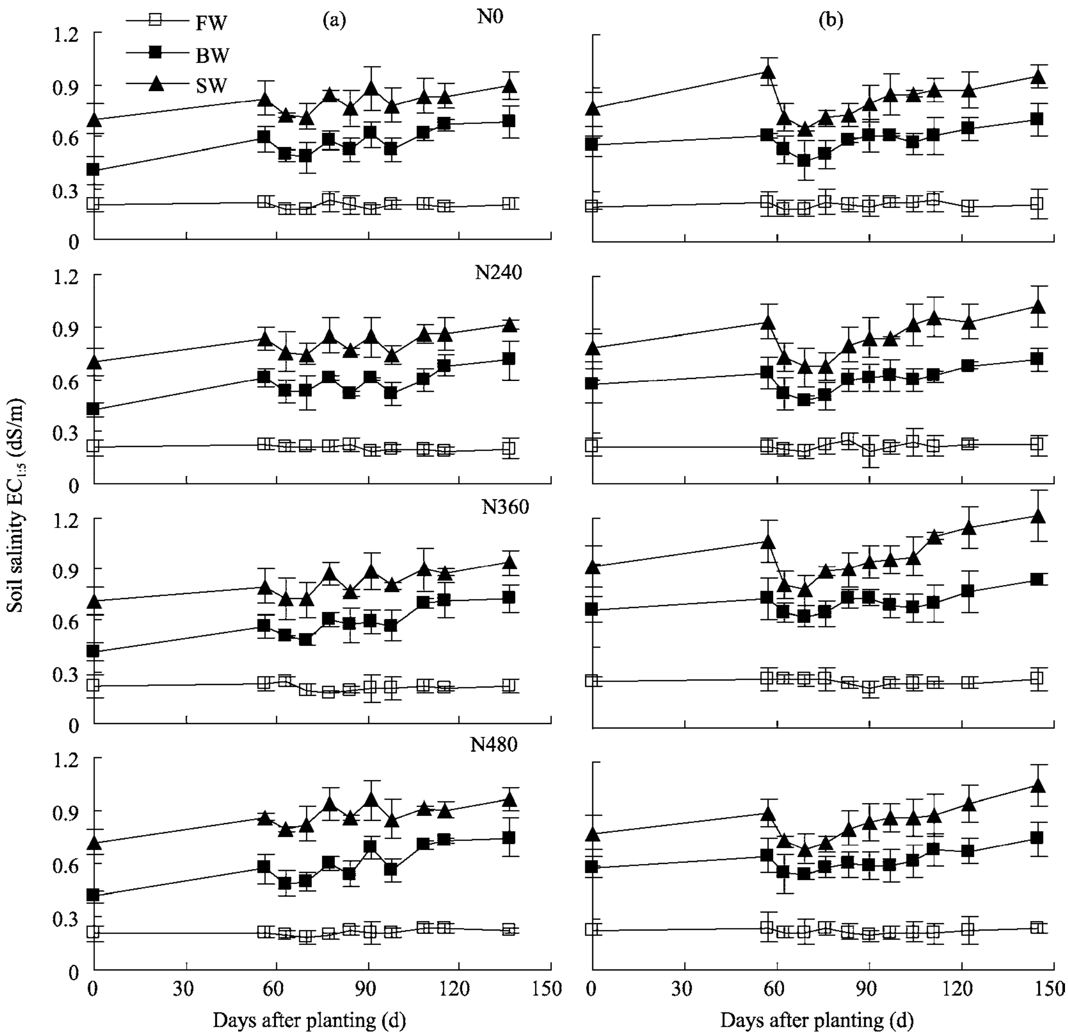


Fig. 4 Average soil salinity ($EC_{1:5}$) in the 0–1.0 m soil profile under different water salinities in 2011 (a) and 2012 (b). Error bars represent SDs. Measurements were taken one day before irrigation.

Compared with the FW treatment, the average salinity ($EC_{1:5}$) in the 1.0-m soil profile was 189% higher in the BW treatment and 319% higher in the SW treatment at the end of the 2011 growing season. At the end of the 2012 growing season, the average salinity ($EC_{1:5}$) was 218% higher in the BW treatment and 347% higher in the SW treatment than in the FW treatment. This is in agreement with the results obtained by Chen et al. (2010b) and Kang et al. (2010). The decrease in soil salinity 62 DAP in 2012 may have been caused either by rainfall or by leaching due to irrigation.

The N application rate had little effect on soil salinity. Averaged over both years and compared with the N0 treatment, soil salinity ($EC_{1:5}$) in the 1.0-m soil profile was 3% higher in the N240 treatment, 5% higher in the N360 treatment, and 9% higher in the N480 treatment. These increases were not significant. This indicates that N application promotes cotton growth, increases water loss from the soil by evapotranspiration, and leads to reduced leaching of soluble salts from the root zone. Excessive application of N fertilizer has also been reported as a factor contributing to soil salinity. Villa-Castorena et al. (2003) observed that N application rates of 200 kg/hm^2 resulted in salt accumulation at the end of the growing season.

Soil salinity in the 0–1.0 m profile dramatically increased as the salinity of the irrigation water increased (Fig. 5). In plots irrigated with fresh water, soil salinity was highest in the deeper layers (0.6–0.8 and 0.8–1.0 m) and was mostly stable. Soil salinity in the 0–0.6 m depth was lower at cotton harvest than at cotton planting in both growing seasons, but no significant difference was observed between 2011 and 2012. The patterns in the brackish and saline water irrigated plots were different with those in the fresh water irrigated plots. Soil salinities in the 0–1.0 m profiles were higher at cotton harvest than before cotton planting in both seasons. Soil salinities at different depths were also significantly higher in 2012 than those in 2011. Salinity was highest in the 0.4–0.8 m depth and lowest in the surface soil (0–0.2 m depth) before cotton planting. At cotton harvest, soil salinity was highest in the 0.6–0.8 m depth, followed by the 0–0.2 m depth (Fig. 5). Salinity was lowest in the 0.8–1.0 m depth.

The N application rate had no significant effect on the distribution of salinity in the soil profile; however, salinity increased slightly as N application rate increased, especially in the BW and SW treatments (data not shown). Salt mainly accumulated in the 0.6–0.8 m depth, especially in the SW treatment. These observations suggest that irrigation with brackish water and saline water can increase soil salinity in the root zone. In addition, excessive application of N fertilizer can increase the accumulation of salt in the root zone when brackish or saline water is used for irrigation.

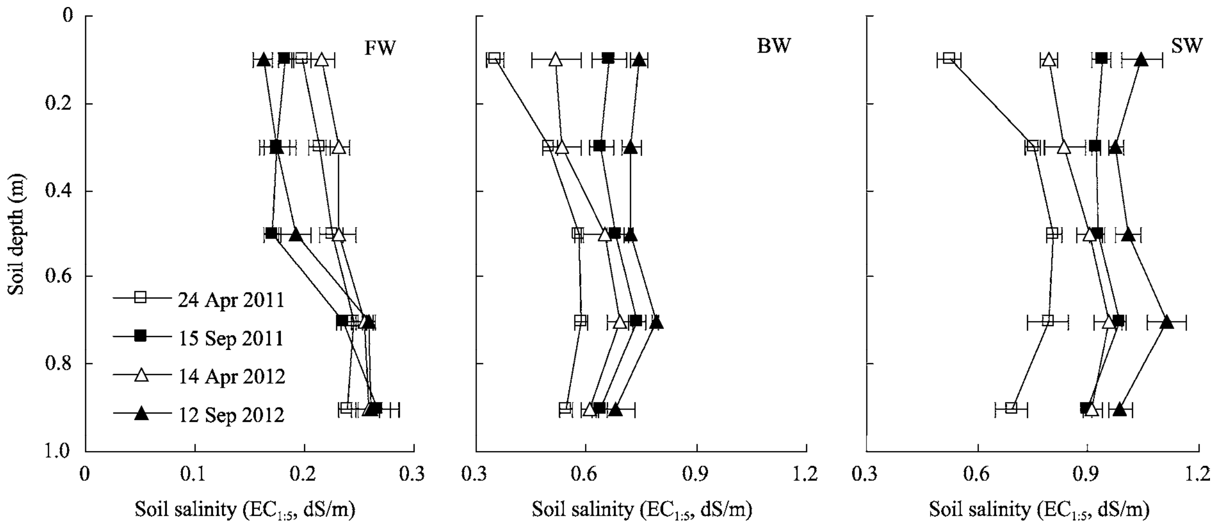


Fig. 5 Soil salinity distribution in the soil profile under different water salinity treatments (N application rate is 360 kg N/hm^2). Error bars represent SDs. Measurements were made before cotton planting (24 April in 2011 and 14 April in 2012) and before cotton harvest (15 September in 2011 and 12 September in 2012).

2.3 Biomass of cotton

Analyses of variance showing the effects of irrigation water salinity and N application on cotton biomass are summarized in Table 3. The biomasses of the cotton plant components were drastically affected by the salinity of the irrigation water. In general, fresh water irrigation always produced the highest biomass. In contrast, cotton biomass decreased as the salinity of the irrigation water increased, regardless of N application rate. Compared with the FW treatment, the BW treatment reduced total cotton biomass by 15% in 2011 and by 23% in 2012. Similarly, the SW treatment reduced total cotton biomass by 33% in 2011 and by 34% in 2012.

In most cases, N application rate had significant effects on the biomass of the plant components in 2011. Biomasses were highest in both cropping seasons when fresh water irrigation was combined with an N application rate of 480 kg N/hm^2 (N480). The total biomass of the cotton plants significantly increased as the N application rate increased in both seasons. Compared with the N0 treatment, the total biomass of the cotton plants were 12%–18% higher in the N240 treatment, 27%–28% higher in the N360 treatment, and 36%–40% higher in the N480 treatment. However, it should be noted that when cotton was irrigated with brackish or saline water, there was no significant difference in total biomass between the N480 treatment and the N360 treatment. In contrast, when cotton was irrigated with fresh water, the total biomass in the N480 treatment was significantly greater than that in the N360 treatment. This observation suggests that applying N fertilizer can enhance cotton biomass regardless of irrigation water salinity; however, high N application rates (>360 kg/hm^2) have no effect on biomass when brackish or saline water is used for irrigation.

Most results in studies about salinity and nitrogen have focused either on salinity as a limiting factor for crop growth (Orak and Ates, 2005; Supanjani and Lee, 2006) or on the N influence on crop growth (Haberle et al., 2006). Related research showed that cotton growth was significantly affected by interaction between soil salinity and N, but not by N alone (Chen et al., 2010a). Some studies also indicate that crop biomass decreased as soil salinity increased (Ashraf and Ahmad, 1999; Esmaili et al., 2008; Gowing et al.,

Table 3 Component biomass and total biomass of cotton plants as affected by irrigation water salinity and N rate in 2011 and 2012

Water salinity	N rate	Biomass (kg/m^2)							
		2011				2012			
		Stem	Leaves	Bolls	Total	Stem	Leaves	Bolls	Total
FW	N0	0.45^{cd}	0.47^{b}	0.74^{f}	1.66^{f}	0.50^{c}	0.52^{b}	0.82^{ef}	1.84^{d}
	N240	0.55^{ab}	0.49^{b}	1.01^{c}	2.05^{c}	0.56^{b}	0.53^{ab}	0.86^{d}	1.95^{c}
	N360	0.59^{a}	0.49^{b}	1.11^{b}	2.19^{b}	0.56^{b}	0.54^{ab}	1.16^{b}	2.25^{b}
	N480	0.61^{a}	0.59^{a}	1.39^{a}	2.59^{a}	0.63^{a}	0.56^{a}	1.35^{a}	2.54^{a}
BW	N0	0.43^{cde}	0.42^{b}	0.68^{fg}	1.53^{g}	0.34^{fg}	0.33^{d}	0.65^{h}	1.32^{g}
	N240	0.47^{bc}	0.43^{b}	0.86^{e}	1.76^{e}	0.39^{de}	0.32^{d}	0.81^{f}	1.52^{e}
	N360	0.49^{bc}	0.45^{b}	0.98^{cd}	1.92^{d}	0.48^{c}	0.41^{c}	0.94^{c}	1.84^{d}
	N480	0.52^{abc}	0.47^{b}	1.01^{c}	2.00^{cd}	0.50^{c}	0.43^{c}	0.94^{c}	1.88^{d}
SW	N0	0.29^{f}	0.30^{c}	0.59^{h}	1.18^{i}	0.32^{g}	0.289^{e}	0.61^{j}	1.22^{h}
	N240	0.35^{ef}	0.33^{c}	0.67^{fg}	1.34^{h}	0.36^{ef}	0.31^{de}	0.77^{g}	1.44^{f}
	N360	0.36^{def}	0.32^{c}	0.83^{e}	1.51^{g}	0.41^{d}	0.29^{e}	0.82^{ef}	1.51^{e}
	N480	0.36^{def}	0.30^{c}	0.89^{de}	1.55^{g}	0.41^{d}	0.29^{e}	0.85^{de}	1.56^{e}
Two-way ANOVA (significance)									
Water salinity (S)		***	***	***	***	***	***	***	***
Nitrogen rate (N)		***	ns	***	***	***	***	***	***
Interaction (S×N)		ns	ns	***	***	**	***	***	***

Note: Different letters in the same column indicate significant differences (P<0.05) between individual treatments. Significance levels: ***, P<0.001; **, P<0.01; ns, P≥0.05.

2009). In contrast, crop biomass increased as N application rates increased (Homaee et al., 2002). Grattan and Grieve (1992) observed that N fertilizer application did not improve plant growth under extreme saline conditions.

2.4 Seed cotton yield

The effects of irrigation water salinity and N application rate on seed cotton yield are summarized in Fig. 6. Seed cotton yield decreased significantly as the salinity of the irrigation water increased. Seed cotton yield in the BW treatment was 10% lower than that in the FW treatment in 2011. Compared with the FW treatment, the BW treatment reduced seed cotton yields by 10% in 2011 and by 16% in 2012 (averaged across the four N application rates). Similarly, the SW treatment reduced seed cotton yields even more, by 23% in 2011 and by 29% in 2012. One explanation for the larger declines in 2012 is that more irrigation water was applied in 2012, causing an increase in soil salinity. Previous studies also indicated that crop yield declined as the salinity of the irrigation water increased (Malash et al., 2008; Gowing et al., 2009; Kang et al., 2010).

The seed cotton yield was also affected by N application rate. Overall, the highest seed cotton yield was observed in the N480 treatment, 42% higher than in the N0 treatment and 18% higher than in the N240 treatment by average. There was no significant difference between the N360 and the N480 treatments. The interaction effect between irrigation water salinity and N application rate on the seed cotton yield was only significant in 2012. In both the FW and BW treatments, seed cotton yield increased significantly as the N application rate increased between 0 and 360 kg N/hm^2 (N360). In contrast, in the SW treatment, there was no significant difference in seed cotton yield among the 240, 360 and 480 kg N/hm^2 treatments.

2.5 Water use efficiency

The effects of irrigation water salinity and N application rate on water drainage, ET, WUE and IWUE are shown in Table 4. In general, water drainage increased sharply as the salinity of the irrigation water increased. Water drainage was by average 55% higher in the BW treatment and 103% higher in the SW treatment compared with the FW treatment. Water drainage was also affected significantly by N application rate. Compared with the N0 treatment, water drainage was 9% less in the N240 treatment, 18% less in the N360 treatment, and 26% less in the N480 treatment.

Evapotranspiration rates declined significantly as the salinity irrigation water increased, but increased as the N application rate increased. In general, irrigation with fresh water always had the highest ET values, being 15% higher than in the BW treatment and 22% higher than in the SW treatment by average. Compared with the N0 treatment, evapotranspiration in 2011 was 3% higher in the N240 treatment, 6% higher in the N360 treatment, and 7% higher in the N480 treatment. In 2012, ET was 3% to 10% higher in the N fertilized treatments than in the unfertilized treatment. Overall, the salinity of the irrigation water had a much larger effect than N application rate on evapotranspiration. This agrees with observations by both

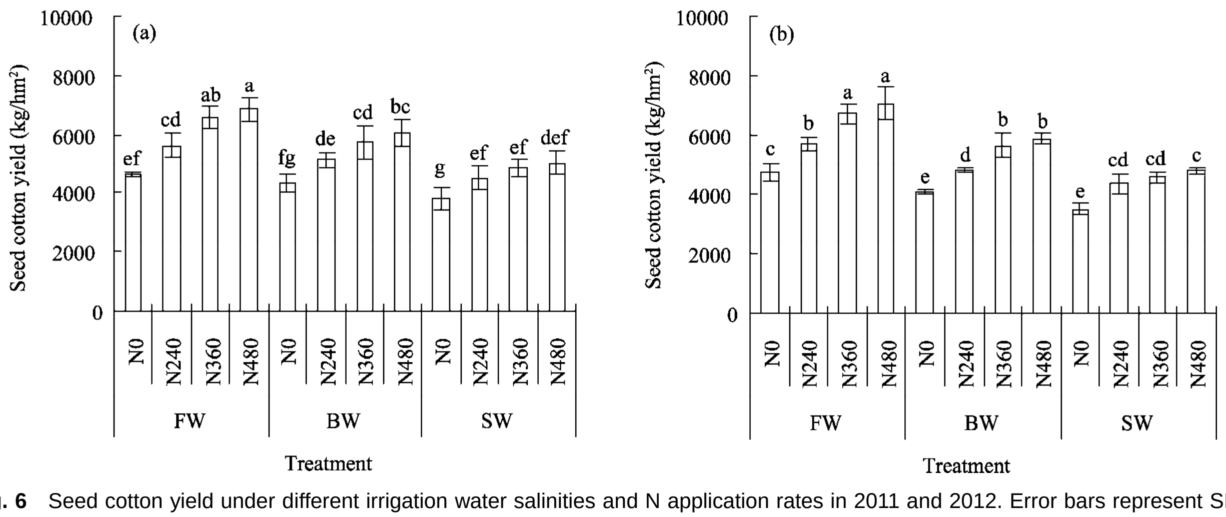


Fig. 6 Seed cotton yield under different irrigation water salinities and N application rates in 2011 and 2012. Error bars represent SDs. Different letters indicate significant differences (P<0.05) between individual treatments.

Table 4 Water drainage, evapotranspiration (ET), water use efficiency (WUE) and irrigation water use efficiency (IWUE) of cotton in 2011 and 2012

Water salinity	N rate	2011				2012			
		Drainage (mm)	ET (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	Drainage (mm)	ET (mm)	WUE (kg/m^3)	IWUE (kg/m^3)
FW	N0	36.9^{f}	567^{b}	0.82^{de}	1.03^{ef}	52.6^{g}	574^{b}	0.82^{c}	0.93^{c}
	N240	31.9^{g}	584^{b}	0.96^{c}	1.24^{cd}	45.7^{h}	593^{b}	0.97^{b}	1.12^{b}
	N360	26.8^{hi}	609^{a}	1.07^{ab}	1.46^{ab}	39.6^{hi}	617^{a}	1.09^{a}	1.32^{a}
	N480	22.4^{i}	613^{a}	1.12^{a}	1.52^{a}	34.7^{i}	636^{a}	1.11^{a}	1.39^{a}
BW	N0	53.5^{c}	514de	0.84^{de}	0.96^{fg}	71.0^{d}	503^{e}	0.81^{c}	0.80^{d}
	N240	50.5^{cd}	520^{cd}	0.99^{bc}	1.14^{de}	66.6^{de}	510de	0.94^{b}	0.94^{c}
	N360	46.3^{de}	527^{cd}	1.08^{a}	1.27^{cd}	60.3^{ef}	527^{cd}	1.07^{a}	1.11^{b}
	N480	42.4^{ef}	535^{c}	1.13^{a}	1.34^{bc}	55.6^{fg}	540^{c}	1.09^{a}	1.15^{b}
SW	N0	70.8^{a}	482^{f}	0.79^{e}	0.85^{g}	95.6^{a}	456^{g}	0.77^{c}	0.79^{e}
	N240	65.5^{a}	499^{ef}	0.90^{cd}	1.00^{ef}	87.2^{b}	473^{fg}	0.92^{b}	0.85^{de}
	N360	59.7^{b}	516^{cde}	0.94^{c}	1.08^{ef}	78.2^{c}	491^{ef}	0.93^{b}	0.90^{cd}
	N480	55.3^{bc}	524^{cd}	0.96^{c}	1.12^{def}	72.8^{cd}	502^{e}	0.95^{b}	0.94^{c}
Two-way ANOVA (significance)									
Water salinity (S)		***	***	***	***	***	***	***	***
Nitrogen rate (N)		***	***	***	***	***	***	***	***
Interaction (S×N)		ns	ns	ns	ns	ns	ns	ns	ns

Note: Different letters in the same column indicate significant differences ($P<0.05$) between individual treatments. Significance levels: ***, $P<0.001$; ns, $P\geq0.05$.

Heidarpour et al. (2009) and Jiang et al. (2012) who reported that the actual evapotranspiration of a crop decreased as the salinity of the irrigation water increased.

Water use efficiency of cotton ranged from 0.79 to 1.13 kg/m^3 in 2011 and from 0.77 to 1.11 kg/m^3 in 2012. The WUE was significantly affected by the salinity of the irrigation water. The WUEs of the FW and BW treatments were similar and about 11% higher than that of the SW treatment. The N application rate also significantly affected WUE. Overall, WUE was highest in the N480 treatment, being 31% higher than in the N0 treatment and 12% higher than in the N240 treatment. There was no significant difference in WUE between the N360 and N480 treatments.

Irrigation water use efficiency (IWUE) of cotton ranged from 0.85 to 1.52 kg/m^3 in 2011 and from 0.79 to 1.39 kg/m^3 in 2012. Both irrigation water salinity and N application rate affected IWUE. Furthermore, the effects were consistent with the effects on WUE during both growing seasons. In the FW and BW treatments, both WUE and IWUE increased significantly as the N application rate increased from 0 (N0) to 360 kg N/hm^2 (N360). In contrast, in the SW treatment, WUE and IWUE remained nearly the same as the N fertilizer rate increased from 240 kg N/hm^2 (N240) to 480 kg N/hm^2 (N480). This trend is consistent with observations for biomass and seed cotton yield. Interactive effects between irrigation water salinity and N application rate on WUE and IWUE were not significant in either growing season. Jiang et al. (2012) investigated the effects of irrigation rates and water salinity on water consumption and water productivity of spring wheat from 2008 to 2010. Their investigation showed that the effects of water salinity on WUE and IWUE were insignificant in 2008 and 2009. However, in 2010, WUE and IWUE in high water salinity treatment (6.1 dS/m) were significantly less than those in low (0.65 dS/m) and moderate (3.2 dS/m) water salinity treatments. Overall, brackish water (4.61 dS/m) irrigation had no significant effect on the WUE of cotton, whereas saline water (8.04 dS/m) irrigation reduced WUE. In addition, increasing N application rates (0–360 kg N/hm^2) increased WUE and IWUE when the cotton was irrigated with either fresh water or brackish water.

2.6 Nitrogen uptake and apparent N recovery

Nitrogen uptake by different components of the cotton plants (stem, leaves and bolls) was significantly affected by salinity of the irrigation water, N application rate and interaction between both factors (Table 5). In 2011, N uptake by stems and leaves was highest in the BW treatment, followed by the FW treatment. In contrast, N uptake by bolls decreased in the order of FW>BW>SW. On average, total N uptake was 20% higher in the FW treatment and 16% higher in the BW treatment than in the SW treatment. There was no significant difference in total N uptake between the FW and BW treatments. In 2012, the N uptake of all components of the cotton plant (stem, leaves and bolls) decreased significantly as the salinity of the irrigation water increased. Total N uptake was highest when plants were irrigated using fresh water, regardless of N application rate. Average total N uptake in the FW treatment was 23% higher than that in the BW treatment and 52% higher than that in the SW treatment.

Nitrogen uptake by all components of the cotton plants increased significantly as N application rate increased in both seasons. Averaged across both growing seasons, total N uptake was 132% higher in the N240 treatment, 184% higher in the N360 treatment, and 215% higher in N480 treatments than in the N0 treatment. The N application rate had less effect on N uptake when either brackish water or saline water instead of fresh water was used for irrigation.

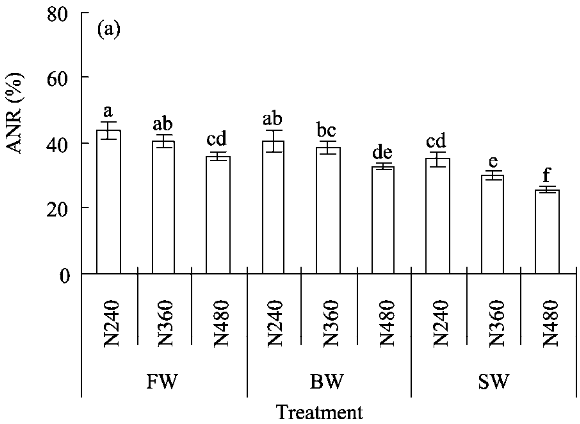
The apparent N recovery (ANR) of the cotton ranged from 26% to 44% in 2011 and from 25% to 47% in 2012 (Fig. 7). In 2011, salinity of the irrigation water, N application rate and their interaction all had significant effects on ANR. Average ANR in the FW treatment was 8% higher than that in the BW treatment and 32% higher than that in the SW treatment. In general, ANR decreased as N application rate increased. The average ANR decreased from 40% in the 240 kg N/hm^2 (N240) treatment to 36% in the 360 kg N/hm^2 (N360) treatment and 32% in the 480 kg N/hm^2 (N480) treatment. There was no significant difference between the FW and BW treatments under the same N application rate, but ANR decreased significantly when plants were irrigated with saline water.

In 2012, the ANR of cotton was significantly affected by the salinity of the irrigation water and the N application rate, but not by their interaction. On average, ANR decreased from 44% in the 0.35 dS/m (FW) treatment to 37% in the 4.61 dS/m (BW) treatment and 29% in the 8.04 dS/m (SW) treatment. The ANR decreased in the order of N240>N360>N480.

Table 5 Nitrogen uptake by cotton plant components in different irrigation water salinities and N rate treatments in 2011 and 2012

Water salinity	N rate	N uptake of the cotton plant (g/m^2)							
		2011				2012			
		Stem	Leaves	Bolls	Total	Stem	Leaves	Bolls	Total
FW	N0	0.70^{d}	1.95^{f}	3.58^{g}	6.23^{f}	1.48^{fg}	3.85^{f}	4.81^{e}	10.14^{h}
	N240	1.49^{c}	5.02^{e}	10.21^{ef}	16.72^{d}	2.89^{c}	7.99^{c}	10.66^{cd}	21.53^{d}
	N360	1.93^{a}	6.85^{c}	12.05^{b}	20.83^{b}	3.33^{b}	9.10^{a}	13.99^{b}	26.42^{b}
	N480	1.98^{a}	7.57^{b}	13.96^{a}	23.51^{a}	3.55^{a}	9.32^{a}	16.72^{a}	29.60^{a}
BW	N0	0.72^{d}	2.13^{f}	3.66^{g}	6.51^{f}	1.04^{h}	2.96^{g}	4.00^{e}	7.99^{i}
	N240	1.78^{b}	5.29^{e}	9.16^{ef}	16.23^{de}	1.48^{fg}	6.73^{d}	9.69^{d}	17.91^{ef}
	N360	2.00^{a}	7.68^{b}	10.69^{cd}	20.37^{b}	1.78^{e}	8.51^{b}	11.29^{c}	21.57^{d}
	N480	1.96^{a}	8.39^{a}	11.92^{bc}	22.27^{a}	2.15^{d}	8.73^{b}	13.03^{b}	24.01^{c}
SW	N0	0.58^{e}	2.02^{f}	3.53^{g}	6.13^{f}	0.89^{h}	2.22^{h}	3.77^{e}	6.88^{i}
	N240	1.43^{c}	4.94^{e}	8.20^{f}	14.57^{e}	1.41^{g}	3.77^{f}	9.62^{f}	14.80^{g}
	N360	1.55^{c}	6.27^{d}	9.14^{ef}	16.96^{d}	1.55^{fg}	5.62^{e}	9.99^{cd}	17.17^{f}
	N480	1.73^{b}	6.84^{c}	9.89^{de}	18.47^{c}	1.64^{ef}	6.88^{d}	10.43^{cd}	18.96^{e}
Two-way ANOVA (significance)									
Water salinity (S)		***	***	***	***	***	***	***	***
Nitrogen rate (N)		***	***	***	***	***	***	***	***
Interaction (S×N)		**	**	**	**	***	***	***	***

Note: Different letters in the same column indicate significant differences (P<0.05) between individual treatments. Significance levels: ***, P<0.001; **, P<0.01.



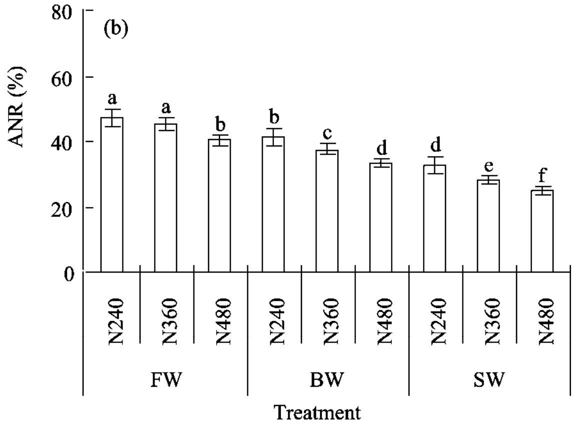


Fig. 7 The apparent N recovery (ANR) of cotton under different treatments in 2011 (a) and 2012 (b). Error bars represent SDs. Different letters indicate significant differences (P<0.05) between individual treatments.

3 Conclusions

Irrigation with either brackish or saline water increased soil salinity. The largest increase in soil salinity was in the SW treatment. Overuse of N fertilizer can lead to the accumulation of salt in the root zone when brackish or saline water is used for irrigation. Brackish water and saline water irrigation reduced evapotranspiration of cotton and increased soil water content in the root zone. This could lead to an increase in the deep percolation of water. Drainage was 55% higher in the BW treatment and 103% higher in the SW treatment than in the FW treatment. This suggested that irrigation with either brackish or saline water might reduce water and fertilizer use efficiency and increase the risk of groundwater contamination.

Cotton yield, water use efficiency and N use efficiency decreased significantly when saline water (8.04 dS/m) was applied by drip irrigation, regardless of N application rate. Thus, highly saline water (EC>8 dS/m) is not appropriate as a single irrigation water resource. Highly saline water might be used as a supplement to replace part of better quality water for cotton irrigation. Brackish water (4.61 dS/m) did not have a profound adverse impact on cotton production, water use efficiency or N use efficiency. Application of 0–360 kg N/hm^2 can reduce salt damage to the crop and increase both cotton yield and water use efficiency. Application of >360 kg N/hm^2 is unnecessary when cotton is irrigated with brackish water.

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