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Soil salinity, sodicity and cotton yield parameters under different drip irrigation regimes during saline wasteland reclamation

Ruoshui Wang[a,*], Shuqin Wan[b], Jiaxia Sun[b], Huijie Xiao[a]

[a] Key Laboratory of State Forestry Administration on Soil and Water Conservation, College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

[b] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

A field trial consisting of cotton grown employing a combination of ridge planting, mulching with film, and drip irrigation was laid out on a plot with severely saline soil in a typical inland arid area of Xinjiang. The effect of five levels of soil matric potential set up 0.2 m below the drip emitter, namely −5 kPa, −10 kPa, −15 kPa, −20 kPa, and −25 kPa, were studied in terms of changes in soil salinity (EC_e), sodicity (SAR), crop growth and yield components. Drip irrigation increased the leaching of soil salts and decreased the EC_e and SAR of each soil layer. Although the levels of soil salt rose again, in spring and winter, after irrigation was discontinued, the root zone (0–40 cm) remained less saline: the EC_e and SAR value under the soil matric potential of −5 kPa and −10 kPa were 63% and 49% of its values in 2009 respectively, before the land was brought under cultivation ($p \leq 0.05$), showing maximum leaching. The yield of cotton peaked at the soil matric potential of −5 kPa. The germination rate, which was the main factor that influenced the cotton yield, was 67% of that in non-saline soil in the first two years, and increased to 84% in the third year. After three years, the rate of germination in all the treatments exceeded 67%, and the highest rate (78%) was at −5 kPa; in the same treatment, boll yield was 4.40 g per plant. Except for germination rate and the yield of lint and seed, all the yield components increased significantly ($p \leq 0.05$) as EC_e and SAR decreased in 2010 and 2011. The correlation between soil salt (salinity and sodicity) and other components such as the number of cotton bolls per plant, the average weight of a boll, and lint percentage varied, probably because water supply was being regulated and, as a result, the physico-chemical properties of the soil kept changing constantly. Taking into account the extent of leaching, crop growth, and yield, the lower limit for the soil matric potential should be −5 kPa at 20 cm below the dripper for the first three years during reclamation to promote cotton cultivation on the saline-sodic soil of Xinjiang.

1. Introduction

Saline wasteland is found all over the world, and China is probably the country with the largest area of such salt-affected soils. Various types of saline soils occur in north-western, northern, and north-eastern China and in its coastal areas (Zhang et al., 1994; Li et al., 2005). The total area of salt-affected soils in Xinjiang – the largest in the country and accounting for one-third of the total – is 8.5×10^4 km². Because the region is land-locked, the process whereby salt residues are formed and accumulate in soil is intensive, and 32.6% of the total cultivated land in Xinjiang shows secondary soil salinization (Wang et al., 1993; Tian et al., 1999). Xinjiang is the main production area of cotton in China, but soil salinization has reduced cotton production drastically, resulting in losses amounting to about US$0.5 billion annually, or about 8% of the total output from farming (Yang et al., 2013; Hu et al., 2012). Therefore, measures are needed urgently to make the saline wasteland in Xinjiang suitable for cultivation.

The most common salt-affected soils in Xinjiang are saline soils of electric conductivity (EC_e) > 4 dS m^{-1} and pH < 8.5. Current methods of treating the soils mainly include using chemicals, growing plants that are adapted to such soils, and using sand as a soil amendment, but these methods are expensive and take a long time to give desired results (Qadir et al., 2001; Oster and Shainberg, 2001). Combining irrigation and drainage to remove the salt by leaching is widely practiced not only in China but also worldwide (Wang et al., 1993; Oster and Jayawardane, 1998). However, Xinjiang lies in an arid area: precipitation is scanty and evaporation is intense, which is why irrigation, when used inappropriately for leaching salt, often leads to

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[*] Corresponding author.
E-mail address: wrsily_2002@163.com (R. Wang).

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Table 1
Salt and ion content of soil before start of the reclamation experiment in 2009 (initial values).

Soil depth (m)	Anion content (g/kg)			Cation content (g/kg)				Total dissolved solids (%)	EC_e (dS/m)	pH	SAR $[(mmol_c\ L^{-1})^{0.5}]$
	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+				
0–0.4	0.27	9.18	0.41	0.19	0.11	0.010	4.90	1.51	45.3	7.42	41
0.4–0.8	0.32	4.33	0.27	0.08	0.09	0.007	3.58	0.87	28.6	7.64	23
0.8–1.2	0.34	3.50	0.25	0.06	0.07	0.007	2.92	0.71	15.4	7.68	30

secondary salinization. Moreover, the high concentration of sodium in relation to other cations in saline soils usually causes aggregate dispersion and poor soil infiltration rate, which may lead to waterlogging in cotton fields (Dodd et al., 2010). Therefore, the traditional surface irrigation for the purpose not only requires copious quantities of water and efficient drainage but also makes leaching less effective: in saline-sodic soils with soluble electrical conductivity (EC_e) of more than 4 dS/m and ESP (exchangeable sodium percentage) more than 15%, particles expand on contact with water, thereby decreasing the porosity and water conductivity of soil, resulting in a very low rate of soil infiltration (White, 2006).

The key to exploit saline soils is to maintain a relatively high soil osmotic potential around the root zone, to make the soil reasonably porous, and to make the soil moisture moving downward. Drip irrigation allows water to be applied more frequently, in small quantities, and over a long time, which maintains the soil matric potential (SMP) around the root zone at higher levels to compensate for the reduced soil permeability resulting from high soil salinity and sodicity, thereby facilitating the absorption of water by plant roots—which is why drip irrigation is widely used in improving saline and saline-sodic soils (Goldberg et al., 1976; Wang et al., 2007; Wan et al., 2007; Kang et al., 2012). Recently, by controlling soil moisture 20 cm below the drip emitter and combining drip irrigation with planting on ridges and mulching (Wang et al., 2012; Zhang et al., 2013), some progress has been made in improving saline and saline-sodic soils: Sun et al. (2012) demonstrated that keeping the SMP at −5 kPa reduced the salt level in coastal saline soils by 64% in two years; Zhang et al. (2014) reported that maintaining the SMP beneath the dripper at −15 kPa improved the physicochemical properties and nutrient status of a saline-sodic soil in Ningxia Xidatanbaijiang markedly; and Li et al. (2015) used brackish water for drip irrigation in a severely saline coastal land and found that more than 50% of the plants survived when the SMP was −5 kPa for the first year and −10 kPa in the second year. These studies mainly focused on the response of soil salinity, moisture and plant growth (Wang et al., 2014; Li et al., 2016). However, for the commercial cotton grown in Xinjiang, soil salinity and sodicity are two significant causes of the poor performance of commercial cotton. A number of studies have shown the sole effect of soil salinity or sodicity on cotton growth (Dodd, 2007; Zhang et al., 2017), whereas the combined effects especially on yield components under drip irrigation have received little attention. Hence, more investigations are needed on the variation of soil, growth and yield parameters of crops – especially cotton – grown on soils with high salinity and sodicity in Xinjiang under drip irrigation during the period of saline wasteland reclamation.

In view of the above, the present study examined the salt level (salinity and sodicity) at different soil layers in a severely saline soil by controlling the SMP thresholds 0.2 m below the drip emitter and also analyzed its effects on the yield parameters of cotton to provide a theoretical basis for the technology of regulating water through drip irrigation and to promote cotton cultivation in the saline soils of Xinjiang.

2. Materials and methods

2.1. Experimental site

The experimental site was in the Agricultural Comprehensive Development Zone, Karamay City, Xinjiang (45°22′–45°40′ N, 84°50′–85°20′ E), part of the lacustrine plain on the north-western rim of the Junggar basin and 20 km from Karamay city. The elevation is 370 m. The region enjoys a typical temperate continental arid desert climate. The average annual precipitation is 105.3 mm whereas the annual potential evaporation is as high as 1269 mm. The area is low lying, the depth of the water table is 2.0–3.0 m, and the soil is mostly the swamp soil from the lacustrine material and saline soil from sedimentary materials. The soil at the experimental site belongs to the chloride-sulfate saline soils category with 1.51% salt, which places the soil in the severely saline grade according to the classification standard for saline soils in China (Wang et al., 1993).

The ion composition and the EC_e of a saturated soil extract (taking the soil from three layers, namely 0–0.4, 0.4–0.8, and 0.8–1.2 m) were determined in 2009, before beginning the experiment. The results are shown in Table 1. For soil samples obtained at the 0.4 m depth at the experimental site, the EC_e and sodium adsorption ratio (SAR) were 45.3 dS/m and 41 $(mmol_c\ L^{-1})^{0.5}$ respectively, which far exceeded the threshold salinity and sodicity for cotton (Maas and Hoffman, 1977; Abrol and Bhumbla, 1979). The major cation in all the three layers was Na^+, which accounted for 32%–65% of the total salts; the main anion was Cl^-, which accounted for 20%–60% of the total. The pH of the entire profile (0–120 cm) at the experimental site varied from 7.4 to 7.7. The local source of irrigation was the reservoir from the western suburbs (the primary source being the Ertix River), and the total dissolved solids (TDS) of the water was 0.2 g/L. Groundwater in the test area was saline, with TDS as high as 31.2 g/L. The field capacity in 0–0.4 m and 0.4–0.8 m soil depths for the experimental soil were 0.31 and 0.29 $cm^3\ cm^{-3}$, respectively.

2.2. Experimental design and arrangement

2.2.1. Experimental design

The experiments spanned three cotton-growing seasons (2009, 2010, and 2011). The variety was Xinluzhong 26, a common variety in the area. The crop was drip irrigated and the SMP of soil 0.2 m directly underneath the drip emitter was set to different levels. The SMP levels that triggered irrigation follow: −5 kPa (S1), −10 kPa (S2), −15 kPa (S3), −20 kPa (S4), and −25 kPa (S5). The experiment was laid out in a completely randomized block design with three replications. A tensiometer was installed in the second replicate to observe the matric potential of soil at a point 20 cm below the drip emitter (Fig. 1).

2.2.2. Experimental arrangement

The management practices for the crop consisted of ridge planting, mulching with film, and drip irrigation. The ridges were 0.4 m wide, 0.15 m high, and 3.8 m long, spaced 0.8 m apart. Each ridge had its separate drip line and accommodated two rows of cotton, spaced 0.2 m apart, with plants within each row spaced 0.1 m apart. Each plot, occupying 30.4 m^2, consisted of 10 ridges with 10 drip lines (Fig. 1). The crops were sown on 31 May 2009, 10 May 2010, and 7 May 2011. Each

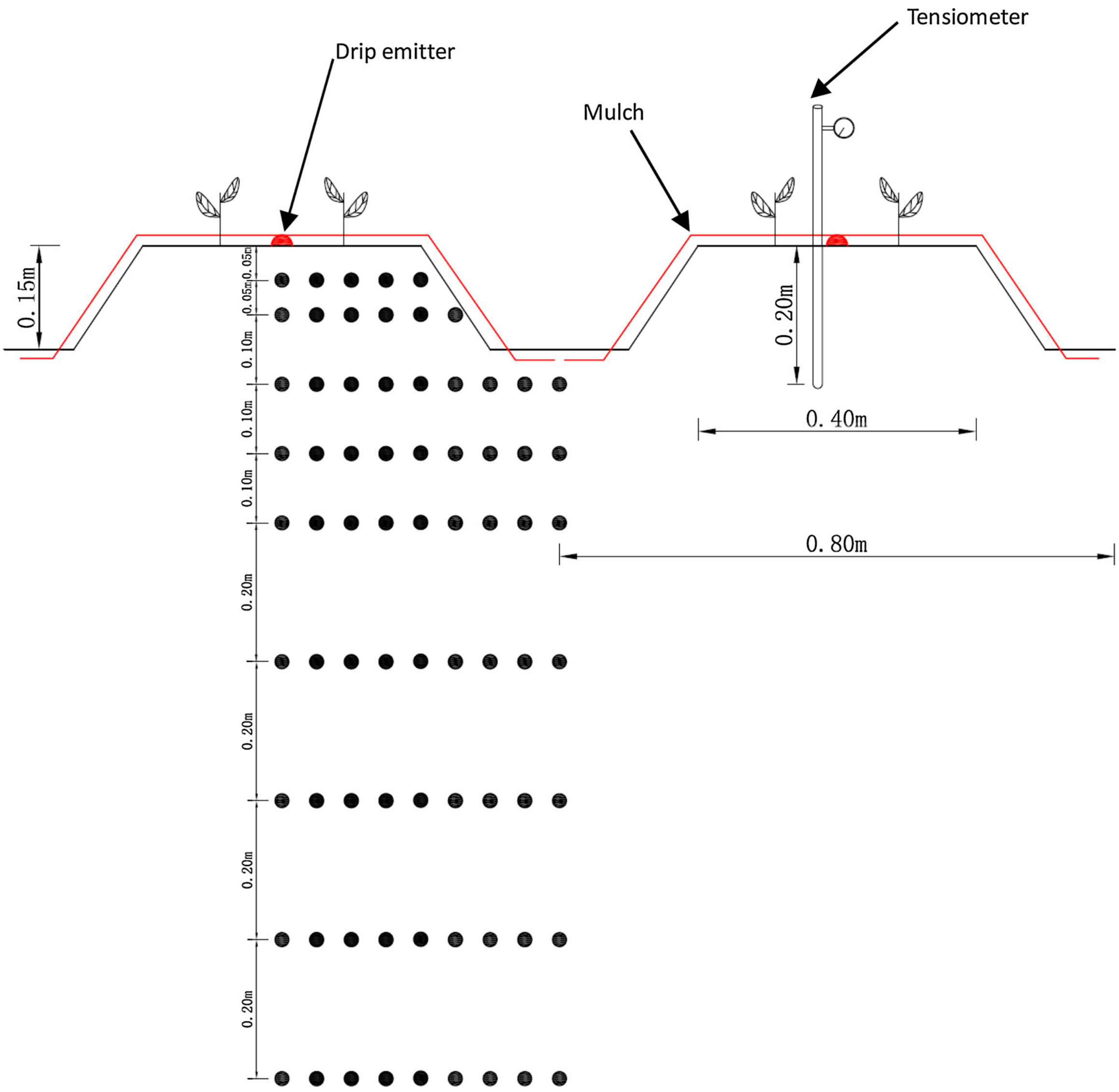

Fig. 1. Experimental set-up and positions of sampling locations.

treatment was regulated by its own separate gravity-fed drip irrigation system, the flow of water being controlled with a ball valve at the bottom of a 1.0 m tall barrel with the capacity to hold 900 L. The flow index of the dripper at the drip irrigation hose was 0.5, the distance between two dippers was 0.2 m, and the flow rate was 0.40–0.56 L/h during the experiment. A compound fertilizer (16% N, 35% P_2O_5, and 8% K_2O; 450 kg/hm^2) was given by mixing it with irrigation water and 150 kg/hm^2 of potassium fertilizer (K_2O) was given in the form of a spray before sowing. Subsequently, each plot was also given 0.3 L of a 30% solution of urea every 5 days. The plots were mulched with a plastic film after sowing, which was removed after seedling emergence. Initially, 2–3 seeds were sown per hole at a depth of 0.03 m. Irrigation began after the final thinning at the four-leaf stage, and only one plant was left per hole.

To ensure that enough seedlings were available before starting the treatments, all the plots were irrigated before sowing, the quantity of irrigation (9.8 mm) being determined based on the moisture content of the top layer. The lower limit of the SMP 0.2 m below the dripper was set at −10 kPa. After the treatments began, irrigation was controlled by the vacuum gauge: readings were taken at 8:00 and 18:00 every day; if the reading was lower than the lower limit, irrigation was triggered immediately. The total quantity of irrigation was 9.8 mm each event for all the treatments.

2.3. Measurements

2.3.1. Soil sampling

Soil from each of the three ridges for each treatment was sampled twice a year, the actual dates being 20 May and 17 September 2009, 28 April and 16 September 2010, and 13 April and 14 September 2011. For each ridge, the samples were collected from nine layers, distributed as follows: 0–0.05, 0.05–0.10, 0.1–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, and 1.0–1.2 m. Each layer was sampled at nine locations, moving progressively away from the dripper horizontally up to 0.4 m in increments of 0.05 m (Fig. 1). The samples were sealed, air-dried in the laboratory, and ground fine enough to pass through a 1 mm sieve.

2.3.2. Soil water content and seasonal water consumption

The soil samples for water content measurements were obtained with an auger (0.02 m in diameter and 0.15 m high) in the same positions as above. The water contents were measured by gravimetric method at intervals of 25–30 d during the cotton growing seasons of 2009–2011.

Seasonal water consumption or actual crop evapotranspiration (ET_a, mm) for cotton in each treatment were estimated using a water balance approach (James, 1988):

$$ETa = I + P \pm C \pm \Delta S - R - D \tag{1}$$

where, I is irrigation amount (mm), P is precipitation (mm), C is capillary rise to the root zone (mm), ΔS is the change of soil water storage (mm), R is surface runoff, and D is percolation (mm).

In Eq. (1), C was considered zero because the water-table depth was 2.0 m below the ground surface. Runoff was assumed to be insignificant because the field was flat. Deep percolation was considered negligible because soil water contents (SWC) below 0.6 m (measurements were up to 1.2 m depth) did not reach field capacity at any sampling time. To estimate ΔS, SWC in the soil profile (down to 0.8 m) was determined by gravimetric measurements. The variations of SWC (ΔS) during the experiment were calculated using the average SWC value of the soil samples.

2.3.3. *Determination of the soil salinity and sodicity*

The EC_e of a saturated extract of soil was measured (Oster et al., 1999) using a conductivity meter (DDS-11A, Ningbo Biocotek Scientific Instrument Co., Ningbo, China). The SAR was calculated from the following equation using concentrations of the subscript cations Na^+, Ca^{2+}, and Mg^{2+} in units of $mmol_c\ L^{-1}$.

$$SAR = C_{Na} / [(C_{Ca} + C_{Mg}) / 2]^{1/2} \tag{2}$$

Concentrations of Na^+ were determined by flame photometer method, and of Ca^{2+} and Mg^{2+} by EDTA titration method (Bao, 2005).

2.3.4. *Growth and physiological indicators*

2.3.4.1. Plant height, stem diameter, and leaf area. In 2010 and 2011, plant height and stem diameter were recorded every 10 days for 10 plants from each replication. For leaf area, leaf length and width were measured in these 10 plants, also every 10 days, until the end of the growth period.

2.3.4.2. Biomass. In mid-September of 2010 and 2011, 10 plants were selected from each replicate to determine the number of cotton bolls at the time of harvest (late October), and the weight (dry weight) of the entire plant and that of all the bolls on it were recorded.

2.3.4.3. Yield. Harvesting was done by hand. The harvest lasted from early October to mid-November, the pickings in each plot being repeated every 7–10 days. Seed yield was recorded for each plot and lint percentage was recorded by ginning 1 kg of seed cotton from each plot.

2.3.5. *Data analysis*

Surfer ver. 7.0, SPSS ver. 16.0, and Excel 2010 were used for data analysis. Analyses of variance were used to test the significance of treatment, growing year and soil layer ($p < 0.05$), differences of treatments, growing years and soil layers combinations were further evaluated by least significant difference (LSD). Because of the different depth intervals, the average value (weighted average) was used in the data analysis.

$$\textit{Weighted average} = \Sigma\ (\textit{sample content} \times \textit{sampling depth or analytical depth}) \tag{3}$$

3. Results

3.1. *Water-table depth*

The water-table depth in the experimental field during cotton growth seasons in 2010 and 2011 are presented in Fig. 2. The main factors likely to influence ground water are precipitation and irrigation in the area. From 29 July (flowering stage) to 5 November (after harvest) in 2010, the water table rose from −3.1 to −2.7 m. During winter 2010 and early spring 2011, the water table receded to −3.2 m. However, the water table rose from −3.1 to −2.6 m during the whole cotton-growing season in 2011 and depths fluctuated more frequently than in 2010 (Fig. 2), possibly because of more intense rainfall in 2010. Moreover, the large amount of flood irrigation water used in non-salinized cotton fields around the experimental area may have raised the water table.

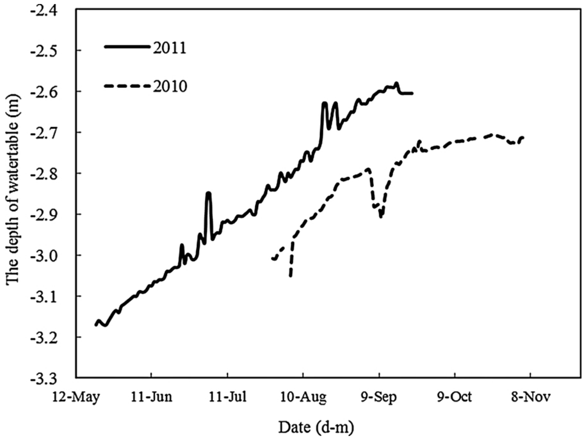

Fig. 2. Water-table depth during growing seasons of cotton in 2010 and 2011. The depth of groundwater table was monitored with an observation well installed in the experimental filed. The observation well consisted of 3.5 m long plastic pipe with a diameter of 4 cm.

3.2. *Soil texture and bulk density*

The soil texture at the experimental site was silt in each soil layer before sowing in 2009 (Table 2). During the three years of irrigation, there were slight changes in soil texture. The soil textures remained as silt in each depth (0–1.2 m) but with minor changes in soil mechanical composition (Table 2). Compared with soil texture, the changes in soil bulk density (SBD) were more significant during the three years of reclamation. For the S1 treatment, SBD decreased significantly by 6% and 8% in 0–0.4 m and 0.4–0.8 m layers, respectively, after three years of irrigation. However, SBD increased for both S1 and S5 treatments in the deep layer (0.8–1.2 m) compared with the initial value in 2009. Although there was a slight but non-significant ($p > 0.05$) decrease of SBD in the 0–0.4 m layer for the S5 treatment in 2011.

Table 2
Soil texture and bulk density at the experimental site before sowing in 2009 and after harvest in 2011.

Year	Soil layers (m)	Soil mechanical composition (%)			Soil texture	Soil bulk density (g/cm^3)
		< 0.002mm	0.002-0.05mm	0.05-2mm		
2009 ^{1*}	0-0.4	1.18	93.48	5.34	Silt	1.33^A
	0.4-0.8	1.03	98.97	0.00	Silt	1.43^B
	0.8-1.2	0.54	95.39	4.07	Silt	1.47^B
2011 ^{2*}	0-0.4	1.46	90.51	8.03	Silt	1.25^B
	0.4-0.8	1.32	94.27	4.41	Silt	1.32^C
	0.8-1.2	1.20	96.89	1.91	Silt	1.53^A
2011 ^{3*}	0-0.4	1.21	91.16	7.63	Silt	1.32^A
	0.4-0.8	1.12	92.66	6.22	Silt	1.49^A
	0.8-1.2	0.92	95.37	3.71	Silt	1.51^A

Note: 1*, before sowing in 2009; 2*, after harvest in 2011 for S1 treatment; 3*, after harvest in 2011 for S5 treatment; A, B, and C represent significant differences ($p < 0.05$) among different treatments and years in the same soil layer.

Table 3
Total quantity, and frequency of irrigation and water consumption (ETa) for each treatment in 2009, 2010, and 2011.

Year	Treatment	Number of irrigations	Irrigation amount (mm)	Seasonal water depth vs. control (%)	Water consumption (ETa, mm)
2009	S1(−5 kPa)	68	666.4	100	679.1^{a}
	S2(−10 kPa)	47	460.6	69	513.2^{b}
	S3(−15 kPa)	30	294.0	44	321.8^{c}
	S4(−20 kPa)	28	274.4	41	301.4^{d}
	S5(−25 kPa)	26	254.8	38	279.8^{d}
2010	S1(−5 kPa)	65	637.0	100	659.6^{a}
	S2(−10 kPa)	47	460.6	72	502.1^{b}
	S3(−15 kPa)	38	372.4	58	391.7^{c}
	S4(−20 kPa)	37	362.6	57	374.6^{d}
	S5(−25 kPa)	25	245.0	38	310.4^{e}
2011	S1(−5 kPa)	66	646.8	100	664.3^{a}
	S2(−10 kPa)	56	548.8	86	516.4^{b}
	S3(−15 kPa)	38	372.4	58	383.8^{c}
	S4(−20 kPa)	28	274.4	44	296.9^{d}
	S5(−25 kPa)	24	235.2	38	253.2^{e}

Note: a, b, c, d and e represent significant differences ($p < 0.05$) among different treatments in the same year.

3.3. Irrigation and seasonal water consumption

The amount of irrigation and the number of irrigations are shown in Table 3. Irrigation treatments were initiated on 15 June 2009 (15 days after seeding), 2 June 2010 (22 days after seeding), and 5 June 2010 (27 days after seeding), which corresponded to the days the seedlings were thinned in each experimental year. The difference between the three years was because of the difference in the seasonal precipitation. The total precipitation (mm) during the whole growth period was 67.3, 114.6 and 70.4, respectively in 2009, 2010 and 2011. The highest irrigation amount was for the S1 treatment during the whole growing season; similarly, the highest ET_a occurred in S1 treatment similarly owing to the adequate soil water supply during the growing season. Therefore, the S1 treatment had the highest total water consumption, 679.1 mm in 2009, 659.6 mm in 2010, and 664.3 mm in 2011. The other treatments were subject to salt stress, which resulted in lower ET_a. The lowest ET_a was for the S5 treatment (−25 kPa): 279.8 mm in 2009, 310.4 mm in 2010, and 253.2 mm in 2011.

3.4. Changes in EC_e

Prior to the 2009 sowing, the salt content in the surface layer was high (EC_e of 45.3 dS/m, Table 4), far higher than the maximum of –7.7 dS/m (Maas and Hoffman, 1977) at which cotton can grow. In the deeper layers, EC_e was significantly lower, indicating that salt accumulated mainly at the surface (0-0.4 m). In the 2009 growing season, the salt was redistributed among the soil layers due to irrigation. When irrigation was discontinued in September 2009, the distribution of salt showed higher values in the surface layer than in the deeper layers, and salt content differed significantly among the layers. By the time the irrigation was terminated, the salt content of all the layers in treatments S1 and S2 was substantially lower than that before sowing. In treatments S3, S4, and S5, the salt content at the surface was lower but that in the deeper layers was higher, probably because the smaller quantities of irrigation in 2009 in these three treatments leached the surface salt layers where it accumulated.

On discontinuing irrigation, the salt moved back to the soil surface as the water evaporated from late winter to early spring, so that salt level in every soil layer in April 2010 was higher than in the corresponding layer in September 2009. Although the salt rebound rates decreased with the decreasing soil layer, the value of EC_e in the 0–0.4 m layers in S1, S2, and S3 continued to be lower than that in the deeper layers, and surface salt levels in S4 and S5 were higher, suggesting that the upward movement of salt is extensive in spring and winter and that inadequate irrigation favors salt accumulation at the surface. On discontinuing the irrigation in 2010, the EC_e value of each soil layer decreased again, indicating that soil mass in the upper layers (0–1.2 m), especially that in the root zone (0–0.4 m), had managed to retain its low-salt status despite the upward movement of salt in spring and winter. The salt content in each soil layer before sowing and after irrigation in 2011 was similar to that in 2010: the EC_e value in the root zone after irrigation was only 4.3 dS/m in S1 and even in S5, it had dropped to 16.1 dS/m, a 63% reduction compared to the value in 2009 before the experiment began. As to the variation in the same layers in different years, the EC_e value in all the layers was the lowest in 2011 and significantly different from that in the other years, suggesting a steady decrease in the salt level over time because of irrigation. Both SMP and the number of years over which the plots had been irrigated affected the EC_e values greatly and so did the interaction between the matric potential and the number of years and that among the matric potential, the number of years, and depths.

3.5. Changes in SAR

The index of SAR represents soil sodicity in the present study. A high SAR (> 13) is reportedly responsible for poor physical properties of the soil, including restricted aeration and moisture movement (Singh and Abrol, 1985). In this study, the changes in SAR with time (Table 5) were similar as those of EC_e (Table 4). Greater reductions of SAR occurred in 0–0.4 m than 0.4–0.8 and 0.8–1.2 m depths. After the third irrigation season, the decline in SAR in the 0–40 cm depth, relative to the initial level, ranged within 10%–38% and the rates increased with increasing SMP thresholds. For treatments S3, S4 and S5, a reduction only occurred in 0–0.4 m depth (Table 5); whereas, for 0.8–1.2 m the final SAR was higher than the initial SAR in 2009. Similar to EC_e, in spring, there were significant rebounds for SAR in each soil depth and the rebounds increased with decreasing SMP threshold. The relative reductions for SAR values were smaller than for EC_e, possibly because of the buffering of exchange capacity. Compared with the initial value in 2009, the values for treatments in root zone after irrigation was terminated showed continued reductions in each growing season. Similarly to EC_e, the effects of SMP threshold, growing years, and soil layers and their interactions all had significant effects on SAR values (Table 5).

By comparing the content after harvest in 2011 with initial values in 2009, the decreasing rates of four main ions (Cl^-, Na^+, Ca^{2+}, and Mg^{2+}) within 0–0.4 m and 0–1.2 m soil depths were calculated (Fig. 3). There were clearly greater rates of decrease for ion contents in shallow (0–0.4 m) than in deep soil layers (0–1.2 m). The decreasing rates of Cl^- content in the two soil layers ranged within 58.3–94.4%, and increased with increasing SMP thresholds. The decrease rates for Na^+ showed similar variations to Cl^-, except for rates in deep soil layers with low SMP thresholds (S3–S5), which ranged within 35.6–55.6%. In contrast, the decrease rates for Ca^{2+} and Mg^{2+} during the three years of reclamation were lower than for Na^+ and Cl–, especially at high SMP thresholds (S1 and S2). After three years of irrigation, the decrease rates for Ca^{2+} and Mg^{2+} in the two soil layers ranged within 25.7–66.8%, and increased with increasing SMP thresholds, similar to those of Cl^- and Na^+.

3.6. Dynamics of cotton growth

3.6.1. Plant height and leaf area index

Plant height exhibited an S-shaped curve from the seedling to the boll stage in 2010 (Fig. 4): a relatively slow initial growth, more repaid growth in the middle of the growth period, and slow growth again towards the end of the growth period. However, growth in 2011 did not

Table 4

EC_e values in different soil layers in each treatment before sowing and after irrigation was discontinued in 2009, 2010, and 2011.

Treatment	Soil depth (m)	EC_e (dS/m)					
		20 May 2009	17 Sept. 2009	28 Apr. 2010	16 Sept. 2010	13 Apr. 2011	14 Sept. 2011
S1 (−5 kPa)	0–0.4	45.3^{Aa}	7.6^{Ccf}	12.4^{Bcf}	6.5^{Cbf}	7.6^{Ccf}	4.3^{Dcf}
	0.4–0.8	22.5^{Ac}	11.6^{Cbf}	19.5^{Bbf}	7.0^{Ebf}	9.5^{Dbf}	7.5^{Ebf}
	0.8–1.2	30.5^{Bb}	21.2^{Caf}	32.4^{Aaf}	10.4^{Eaf}	18.5^{Daf}	11.1^{Eaf}
	0–1.2	32.8^{A}	13.5^{C}	21.5^{B}	8.0^{E}	11.9^{D}	7.8^{E}
S2 (−10 kPa)	0–0.4	45.3^{Aa}	8.4^{Ecg}	26.2^{Ccg}	11.8^{Dcg}	30.8^{Bcg}	12.0^{Dcg}
	0.4–0.8	22.0^{Cc}	12.8^{Ebf}	34.1^{Bbg}	16.2^{Dbg}	40.7^{Abg}	22.7^{Cbg}
	0.8–1.2	30.4^{Cb}	24.7^{Eag}	37.7^{Bag}	29.8^{CDag}	42.9^{Aag}	27.2^{Dag}
	0–1.2	32.6^{B}	15.3^{E}	32.6^{B}	19.3^{D}	38.2^{A}	20.9^{C}
S3 (−15 kPa)	0–0.4	45.3^{Aa}	21.0^{Dch}	36.1^{Cbh}	14.8^{Ech}	40.3^{Bch}	20.1^{Dch}
	0.4–0.8	22.0^{Ac}	38.4^{Cag}	40.3^{Bah}	28.7^{Dbh}	43.8^{Fbg}	25.3^{Ebh}
	0.8–1.2	30.4^{Eb}	34.8^{Dbh}	37.7^{Cbg}	39.9^{Bah}	47.9^{Aag}	27.1^{Fag}
	0–1.2	32.6^{C}	31.4^{D}	38.0^{B}	27.8^{E}	43.6^{A}	24.0^{F}
S4 (−20 kPa)	0–0.4	45.3^{Aa}	23.0^{Dch}	40.2^{Bah}	17.5^{Eci}	32.8^{Ccg}	14.1^{Fbg}
	0.4–0.8	22.0^{Dc}	42.3^{Aag}	38.3^{Bah}	27.1^{Cbh}	38.9^{Bbg}	12.8^{Eci}
	0.8–1.2	30.4^{Eb}	37.8^{Cbh}	32.6^{Dbg}	39.8^{Bah}	43.4^{Aag}	18.4^{Fah}
	0–1.2	32.6^{D}	34.3^{C}	37.0^{B}	28.1^{E}	38.4^{A}	15.1^{F}
S5 (−25 kPa)	0–0.4	45.3^{Aa}	23.1^{Cch}	43.1^{Aah}	19.2^{Dci}	34.9^{Bcg}	16.1^{Dcg}
	0.4–0.8	22.0^{Dc}	42.3^{Aag}	36.9^{Bbg}	28.3^{Cbh}	40.8^{Abg}	24.6^{Dbg}
	0.8–1.2	30.4^{Db}	36.9^{Cbh}	40.4^{Babh}	36.4^{Cah}	44.4^{Aag}	30.5^{Dag}
	0–1.2	32.6^{B}	34.1^{B}	40.1^{A}	28.0^{C}	40.0^{A}	24.1^{D}
	SMP	Year	SMP × Year		Year × Soil layer	SMP × Year × Soil layer	
F value	23.114**	10.347**	2.278*		ns	2.277**	

Note: a, b, and c represent significant differences among different soil layers in the same treatment in the same year; f, g, h, and i represent significant differences among different treatments in the same soil layer in the same year; and A, B, C, D, E, and F indicate significant differences among different years in the same treatment in the same layer. (In each case, $p < 0.05$); ns, non-significant; *, $p < 0.05$; **, $p < 0.01$.

follow that pattern because of greater precipitation (27 mm) in early April and May, which resulted in excessive growth of cotton during that period. In 2010, the treatments involving greater quantities of irrigation (S1 and S2) resulted in rapid growth, whereas the shortest plants were seen in S5. Over time, the level of salt in the soil decreased gradually, as did the differences among treatments. Therefore, the difference in plant height among different treatments was smaller in 2011 than that in 2010. The leaf area index (LAI) also showed a similar S-shaped curve. Because of greater irrigation and sufficient leaching of salt in S1 and S2, the mild saline stress resulted in rapid growth, whereas growth was far slower in S4 and S5, because of the severe salt stress from smaller quantities of irrigation. Irrigation was discontinued after the boll stage,

Table 5

SAR values in different soil layers in each treatment before sowing and after irrigation was discontinued in 2009, 2010, and 2011.

Treatment	Soil depth (m)	SAR$[(mmol_c\ L^{-1})^{0.5}]$					
		20 May 2009	17 Sept. 2009	28 Apr. 2010	16 Sept. 2010	13 Apr. 2011	14 Sept. 2011
S1 (−5 kPa)	0–0.4	41^{Aa}	16^{Ccf}	21^{Bcf}	15^{Cbf}	19^{Bbf}	10^{Dbf}
	0.4–0.8	23^{Ac}	23^{Bbf}	24^{Bbf}	21^{Caf}	22^{Caf}	21^{Caf}
	0.8–1.2	30^{Ab}	26^{Baf}	31^{Aaf}	22^{Caf}	23^{Caf}	22^{Caf}
	0–1.2	31^{A}	22^{B}	25^{B}	19^{C}	21^{B}	18^{C}
S2 (−10 kPa)	0–0.4	41^{Aa}	20^{Ccg}	23^{Bcf}	18^{Ccg}	22^{Bbf}	16^{Dcg}
	0.4–0.8	23^{Bc}	25^{Abf}	27^{Abg}	23^{Bbf}	27^{Aag}	22^{Bbf}
	0.8–1.2	30^{Bb}	29^{Bag}	32^{Aag}	29^{Bag}	33^{Aag}	29^{Bag}
	0–1.2	31^{A}	25^{B}	27^{AB}	23^{B}	27^{AB}	23^{B}
S3 (−15 kPa)	0–0.4	41^{Aa}	24^{Cch}	29^{Bcg}	20^{Dcg}	28^{Bcg}	20^{Dch}
	0.4–0.8	23^{Cc}	29^{Bbg}	33^{Abh}	27^{Bbg}	32^{Abh}	23^{Cbf}
	0.8–1.2	30^{Bb}	31^{Bag}	37^{Aah}	32^{Bah}	37^{Aah}	33^{Bah}
	0–1.2	31^{A}	28^{B}	33^{A}	27^{B}	32^{A}	25^{C}
S4 (−20 kPa)	0–0.4	41^{Aa}	26^{BCbh}	33^{Bbh}	23^{Cch}	32^{Bbh}	23^{Cci}
	0.4–0.8	23^{Dc}	33^{Bah}	38^{Aai}	30^{Cbh}	36^{Aai}	30^{Cbg}
	0.8–1.2	30^{Cb}	34^{Bah}	40^{Aai}	34^{Bah}	40^{Aai}	34^{Bah}
	0–1.2	31^{B}	31^{B}	37^{A}	29^{C}	36^{A}	29^{C}
S5 (−25 kPa)	0–0.4	41^{Aa}	27^{Cbh}	35^{Bbh}	25^{Cch}	33^{Bch}	24^{Cci}
	0.4–0.8	23^{Cc}	34^{Bah}	39^{Aai}	33^{Bbi}	38^{Abi}	32^{Bbg}
	0.8–1.2	30^{Cb}	35^{Bah}	41^{Aai}	36^{Bai}	41^{Aai}	35^{Bah}
	0–1.2	31^{B}	32^{B}	39^{A}	31^{B}	38^{A}	31^{B}
	SMP	Year	SMP × Year	Year × Soil layer		SMP × Year × Soil layer	
F value	13.762**	8.941**	1.893*	ns		2.379*	

Note: a, b, and c represent significant differences among different soil layers in the same treatment in the same year; f, g, h, and i represent significant differences among different treatments in the same soil layer in the same year; and A, B, C, D, E, and F indicate significant differences among different years in the same treatment in the same layer. (In each case, $p < 0.05$); ns, non-significant; *, $p < 0.05$; **, $p < 0.01$.

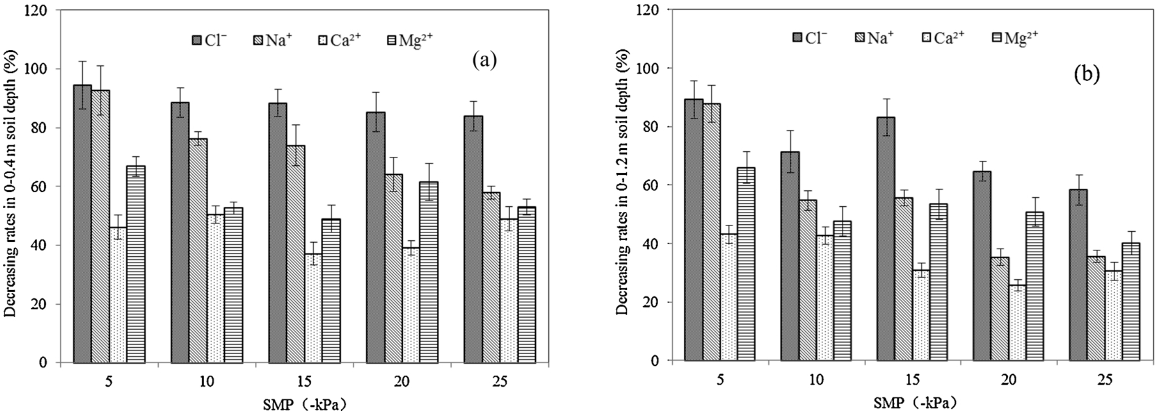

Fig. 3. The decreasing rates (in comparison to initial values in 2009) for the four salt ions contents in 0–0.4 m (a) and 0–1.2 m (b) soil depths after harvest in 2011.

and the LAI decreased because of wilting and even defoliation. Because of the higher precipitation during the early growth period in 2011, the pattern of changes in LAI in each treatment was different from that in the corresponding treatment in 2010, namely more rapid growth at the beginning, which was comparable to the rate seen in mid-term in 2010, and the faster growth in S1 and S2.

3.6.2. Yield and yield components

In the present study, the following attributes were considered as cotton yield components: germination percentage, number of bolls per plant, seed weight per boll, and lint percentage (Table 6). Prior to sowing in 2009, germination was lower than 35% in all the treatments because of high salt content in the soil: all the differences between them were significant, and were also seen in 2010. Because of irrigation in 2009, leaching of salts from the root zone was higher in S1 and S2, which increased the germination percentage in those two treatments, whereas it was relatively low in the other three treatments. In 2011, germination was greatly improved and reached 67% in all the treatments with no substantial difference among them, indicating that the salt had been effectively leached as a result of the previous year's irrigation.

Late sowing, high level of salt, and a local storm in 2009 resulted in higher mortality of cotton seedlings. In October 2009, the maturing of bolls was inhibited owing to an abrupt decrease in temperature, and no yield data could be collected in that year. In 2010, the number of bolls per plant differed significantly among treatments, and decreased with

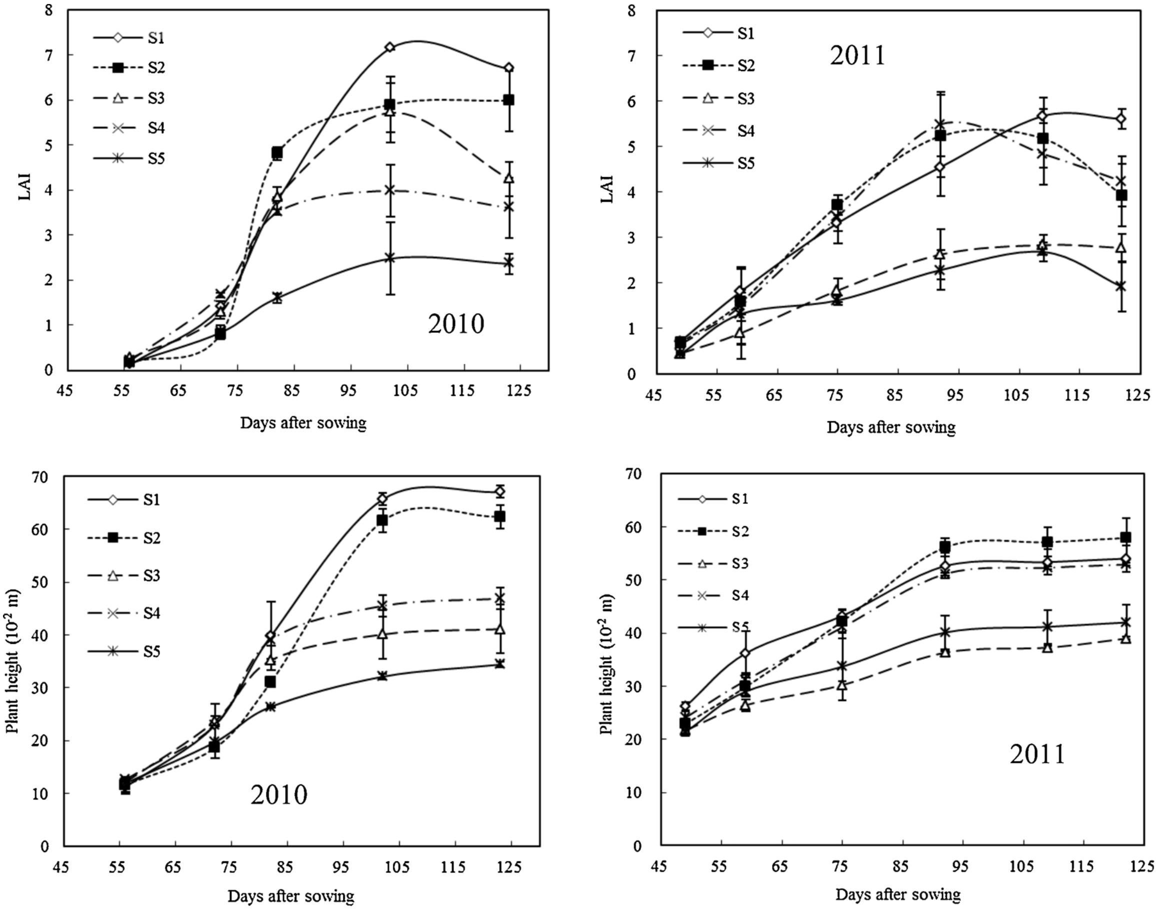

Fig. 4. Changes in leaf area index (LAI) and plant height during growth season in 2010 and 2011.

Table 6
Yield parameters of cotton in different treatments in 2009, 2010 and 2011.

Year	Soil matric potential (−kPa)	Germination (%)	Number of bolls per plant	Seed weight per boll (10^{-3} kg)	Lint percentage (%)	Seed yield (10^3 kg/ha)	Lint yield (10^3 kg /ha)
2009	5	30.5^{ab}	–	–	–	–	–
	10	34.5^{a}	–	–	–	–	–
	15	28.5^{ab}	–	–	–	–	–
	20	34.6^{a}	–	–	–	–	–
	25	21.3^{b}	–	–	–	–	–
2010	5	49.7^{a}	13^{a}	3.05^{b}	34.2^{a}	2.92^{a}	1.00^{a}
	10	43.9^{a}	13^{a}	3.39^{b}	27.3^{ab}	2.31^{ab}	0.63^{ab}
	15	27.6^{b}	9^{ab}	4.65^{a}	25.2^{b}	1.93^{ab}	0.49^{ab}
	20	27.6^{b}	8^{ab}	2.56^{b}	28.1^{ab}	2.08^{ab}	0.58^{ab}
	25	22.4^{b}	6^{b}	2.69^{b}	25.3^{b}	1.31^{b}	0.33^{b}
2011	5	78.1^{a}	8^{c}	4.78^{a}	39.1^{a}	3.65^{a}	1.43^{a}
	10	76.4^{a}	11^{b}	4.56^{a}	38.6^{a}	2.54^{b}	0.98^{b}
	15	72.1^{a}	11^{b}	4.66^{a}	37.5^{a}	2.31^{ab}	0.87^{b}
	20	71.4^{a}	13^{a}	4.63^{a}	35.4^{a}	2.41^{b}	0.85^{b}
	25	67.6^{a}	9^{c}	4.41^{a}	36.1^{a}	1.81^{c}	0.65^{c}

Note: a, b, and c represent significance differences among treatments in the same year ($P < 0.05$).

decreasing SMP. In 2011, the relationship between the number of bolls per plant and the matric potential was not uniform: at the matric potential higher than −20 kPa, the boll number per plant increased as the reduction in SMP, but it decreases as the reduction in SMP was lower than −20 kPa.

In 2010, both seed weight per boll and lint percentage differed significantly among the treatments (Table 6). Initially, up to −15 kPa, seed weight increased as the matric potential increased but decreased as the potential increased beyond −15 kPa. In 2011, the seed weight did not differ substantially among the treatments, although it was much more than that in 2010 in all the treatments, indicating that lower soil salt level had increased the weight per boll and lint percentage to some extent. In 2010, the yield of lint and seed in S1 was 69% of that from a local non-saline soil, and went up to 86% in 2010. In both years, the yields of lint and seed increased as the SMP decreased.

3.7. Soil salt level and yield components

In the present study, the major factors that affected plant growth were soil moisture and salt, but salt was affected mainly by irrigation (Tables 3 and 4); therefore, regression analysis was used to study the relationship between the components of yield and soil salt (salinity and sodicity). Soil salinity and sodicity (EC_e and SAR value) towards the later stages of growth in the top 40 cm layers, based on root distribution as a result of drip irrigation (Hanson et al., 2006; Hu et al., 2009), was taken as the main factor influencing yield because that value was seen to have a significant effect on the growth of cotton.

In 2010 and 2011, germination percentage was significantly and linearly correlated with both soil EC_e and SAR value of the root zone (Figs. 5 and 6), suggesting that salt has a significant effect on germination percentage, whereas no such correlation was seen in 2009. In 2010, the number of bolls per plant decreased with the decrease in EC_e and SAR, showing a significant linear correlation between them. In 2011, however, the number of bolls per plant increased initially with increase in EC_e and SAR, but began to decline as the values reached 16 dS/m and 21 $(\text{mmol}_c\ L^{-1})^{0.5}$. Seed weight per boll, on the other hand, showed the opposite pattern: an initial increase followed by a decrease as the EC_e and SAR values increased beyond a point in 2010, and a negative linear correlation in 2011. In 2010 and 2011, although no significant linear correlation of lint percentage with both EC_e and SAR were seen, lint percentage in 2011 was significantly higher than that in 2010, indicating that a lower salt level increases lint percentage (Ashraf and Ahmad, 2000). The effects of EC_e and SAR levels in the root zone on the yields of lint and seed were dramatic, and both showed a significant linear correlation with EC_e and SAR in 2010 and 2011 (Fig. 7). The yield of lint and seed in 2011 was higher than that in 2010 in all the treatments, with S1 and S5 showing the largest increase, 25% in the case of lint and 42% in that of seed in S1, the corresponding values in S5 being and 42% and 92% (Fig. 7).

4. Discussion

4.1. Effect of SMP thresholds on soil salt

In the saline region of Xinjiang, stress caused by soil salinity and sodicity is the main reason for the restricted growth of cotton. More frequent drip irrigation but in smaller quantities and over a longer duration maintained a higher level of SMP around the dripper and leached the salt ions away from the root zone, compensating to some extent for the lower soil permeability due to high salt levels, and thus led to higher uptake of water. In addition, mulching with a film reduced surface evaporation, thereby promoting the retention of soil moisture and inhibiting the upward movement of salt to the surface. Dou and Kang (2010) used a combination of planting on ridges, mulching, and drip irrigation to study the regulation of soil moisture in the saline-sodic soils of the Pingluo region in Ningxia and demonstrated that soil salt in the root zone was effectively leached away after three years of irrigation, and Jiao et al. (2008) showed that the highest leaching and the highest crop yield were obtained when the SMP was set at −5 kPa during drip irrigation in the Qingtongxia region in Ningxia. In the present study, after three years of irrigation, the EC_e and SAR of soil within the root zone at −5 kPa was only 4.3 dS/m and 10 $(\text{mmol}_c\ L^{-1})^{0.5}$, compared to 16.1 dS/m and 24 $(\text{mmol}_c\ L^{-1})^{0.5}$ at −25 kPa respectively, with lower quantity of irrigation. The value was reduced to 63% of that in 2009, before initiating the experiment, and the soil had already turned into mildly saline soil, as it did in Ningxia (Jiao et al., 2006) and as reported by Wan et al. (2012), indicating that the combination of ridge planting, mulching, and drip irrigation is particularly suitable for the saline wastelands of Xinjiang. Li et al., (2016) found that the optimal threshold of SMP should be −10 kPa for a salt-sensitive plant in a coastal saline region. In our study, more water was applied for the S1 than other treatments, and leached salt from the 0–0.4 m depth in treatments with low SMP thresholds (S2–S5) was more prone to accumulate in 0.4–0.8 and 0.8–1.2 m soil layers. Moreover, because of the lateral and downward movement of water and salt that occurs beneath drip emitters (Wang et al., 2012), significant reductions occurred during each irrigation season followed by a significant rebound during winter. The ratio of lateral movement to downward movement likely increased with decreasing applied water, which would explain why the rebound in salinity was greater for the

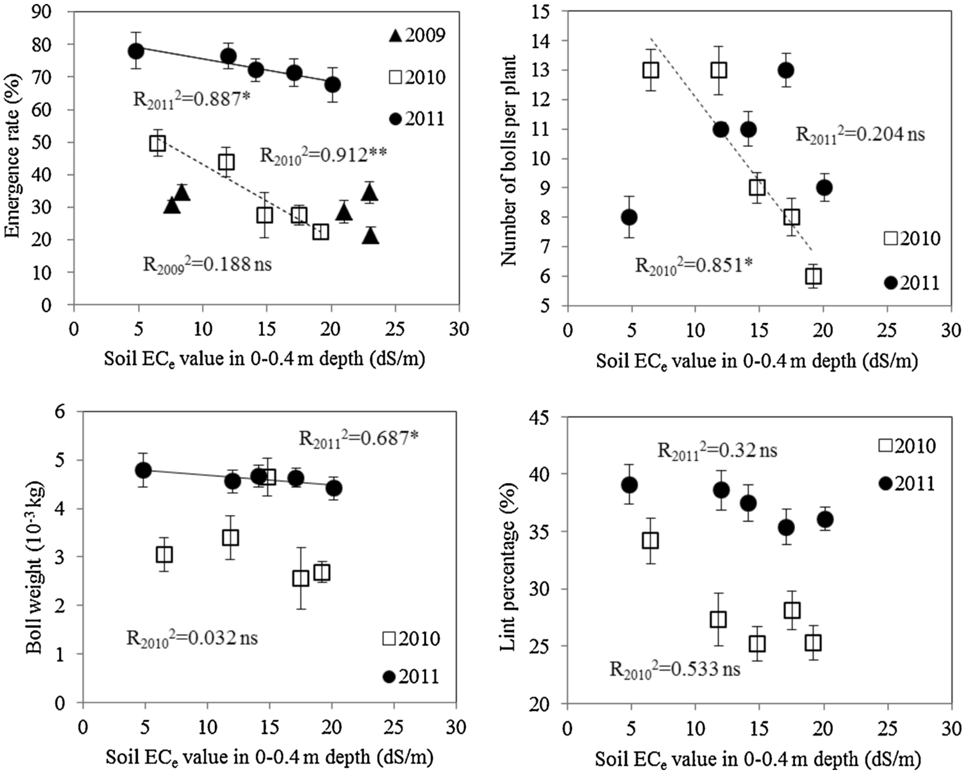

Fig. 5. Correlation between parameters of yield and EC_e values of soil in the root zone (0–40 cm layer) in 2009, 2010 and 2011 (ns, non-significant; *, $p < 0.05$; **, $p < 0.01$).

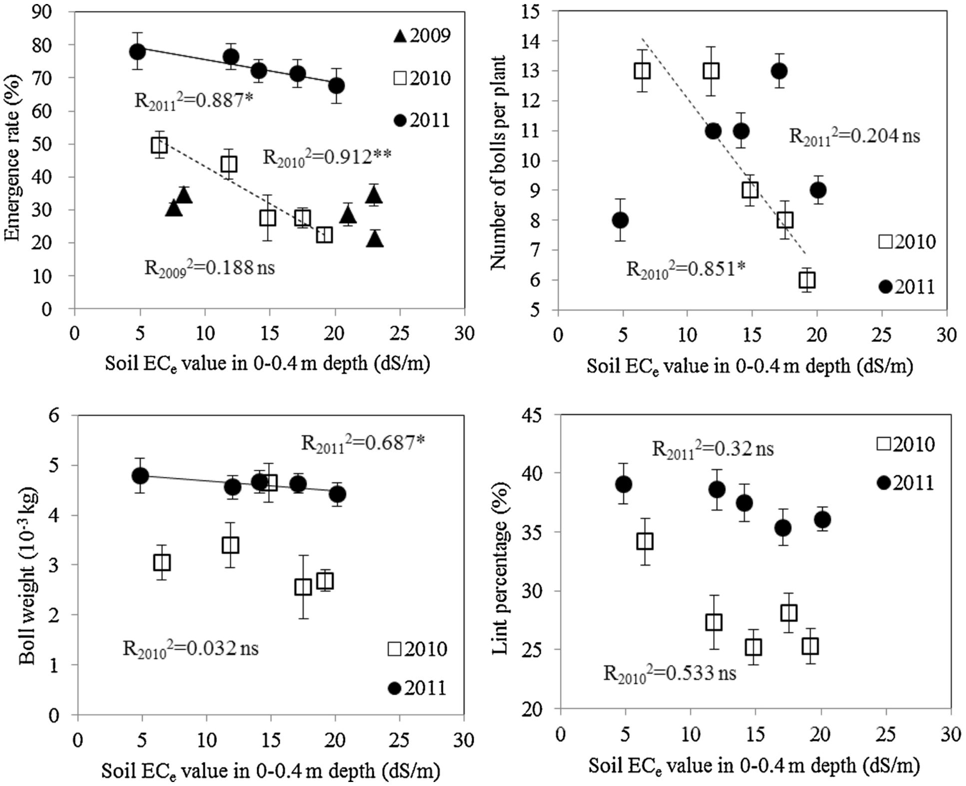

Fig. 6. Correlation between parameters of yield and SAR values of soil in the root zone (0–40 cm layer) in 2009, 2010 and 2011 (ns, non-significant; *, $p < 0.05$; **, $p < 0.01$).

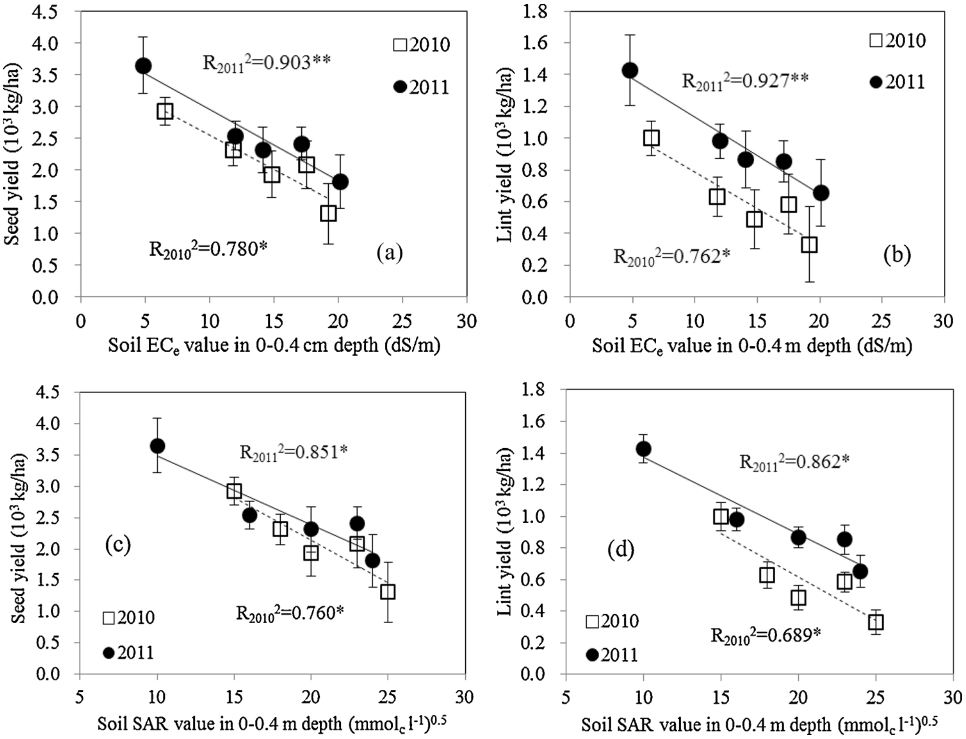

Fig. 7. Correlations between cotton yields and EC_e values (a and b), cotton yields and SAR values (c and d) of soil in the root zone (0–40 cm layer) in 2010 and 2011 (ns, non-significant; *, $p < 0.05$; **, $p < 0.01$).

S2–S5 treatments than the S1. Therefore, the lower limit of −5 kPa for the SMP at 0.2 m below the dripper can serve as a guide and should be used for 3 years before sowing. The difference in the trigger target was that leaching was affected not only by the frequency and quantity of irrigation, but also by the composition of salts, climate, and other farming practices. In the present study, the reductions for SAR values were smaller than for EC_e. This may be because of buffering of exchange capacity (Carmona et al., 2010), which can also be found in the decreasing rates for the four main soil ions after three years of irrigation (Fig. 3) – the decrease rates for Na^+ and Cl^- were much higher than for Ca^{2+} and Mg^{2+}. The mutual effects of soil salinity and sodicity made leaching more difficult than the individual effect of the two. Qadir et al. (2002) found that the H^+ released by roots released Ca from insoluble solid salts as Ca^{2+}, which lowered soil Na^+ because of the ion substitution effect, thereby lowering the SAR in such saline-sodic soils and improving the physical properties of soil – which was one reason for the improved soil condition after three years. In the present study, soil structure improved as shown by SBD (Table 2), especially in the shallow soil layer with high SMP thresholds (S1 treatment).

4.2. *Effects of SMP thresholds on cotton growth*

In severely saline-sodic soils, high salinity and sodicity is the main reason for the poor performance of cotton, including osmotic stress, ion toxicity, ion imbalance, and nutritional deficiency (Fisher et al., 1994). Of these, salt stress is the main factor, which inhibits photosynthesis and lowers carbon assimilation. In addition, the synthesis and accumulation of substances, which, at their normal concentrations, help in osmotic adjustment and the maintenance of osmotic potential, results in greater energy consumption, accelerated senescence—and eventual death due to carbon starvation (Yu and Tang, 1998). The saline-sodic soil in this study area is of the chloride-sulfate type, and salt stress comes mainly from Na^+. In the present experiment, treatments that involved larger quantities of irrigation, namely S1 and S2, resulted in higher growth parameters, whereas salt stress was more severe in the treatment that involved the lowest quantity of irrigation treatment, namely S5, resulting in the shortest plants, which is consistent with earlier results (Bassil and Kaffka, 2002; Chen et al., 2009; Kang et al., 2010). It was noted that high soil sodicity had no effect on the number of bolls and fruit weight but did reduce plant height of cotton (Dodd et al., 2010). However in our study, the combined effects of high salinity and sodicity had an adverse effect on cotton growth especially in the first two years when soil salts were relatively high (Table 6). In S1, the growth peak was delayed compared to that in the other treatments, mainly because of the more copious irrigation and milder salt stress in S1. Compared to other developmental stages, the seedling stage is more sensitive to soil salt (Zhang et al., 2008; Dong et al., 2009). In the experimental region, the salt level was high in 2009, before sowing, which resulted in low germination percentage (< 35%) in all treatments; after three years of irrigation, it increased significantly, to more than 67%, in all treatments, following marked improvement in the physicochemical properties of soil due to adequate leaching of salts, and especially due to the marked increase in soil porosity and nutrient content (Wang et al., 2015).

4.3. *Correlations between soil salt and cotton yield components*

Generally, the major factors that affect plant growth in arid saline land are soil moisture and salt, however, in this study, salt was affected mainly by irrigation (Tables 4 and 5). Therefore, we used regression analysis to investigate the relationships between cotton yield components and soil salt (salinity and sodicity). The results showed that the variation trends of yield components with soil salinity and sodicity were similar. The number of bolls per plant decreased with the decrease in both EC_e and SAR in the root zone, and showed significant linear relationships, consistent with earlier results (Daleshwar et al., 2006; Dağdelen et al., 2009). However, in 2011, the number of bolls per plant increased initially with both EC_e and SAR but declined later as EC_e and SAR reached 16 dS/m and 21 $(\text{mmol}_c\ L^{-1})^{0.5}$ respectively, whereas the weight per boll showed the opposite pattern: an initial increase followed by a decrease as EC_e and SAR increased but showed a significant linear negative correlation to both soil EC_e and SAR in 2011, probably because the gradual reduction in salt over time had changed the main factors affecting reproductive growth of cotton. However, given the increased plant population and the same amount of fertilizers meant that each plant had a smaller share of fertilizers under the high matric potential treatments (low EC_e and SAR value), which, to some extent, affected the reproductive growth of cotton. It was reported that in a salt-affected soil, the decrease in cotton yield was mainly due to reduction in boll number (Zhang et al., 2017). In our study, the main factor that affected cotton yield was probably the germination rate, as the variation trends with soil salt (salinity and sodicity) were similar over the last two years. In S5, soil salt remained the major factor affecting growth because of the relatively high soil salt levels in 2010 and 2011. Differences in the extent of leaching under different SMPs lead to various changes in the physicochemical properties of soil such as porosity and nutrient status, which affect the growth and yield of crops (Rasouli et al., 2013). In the present study, the yield of lint and seed under S1 was 69% of that in non-saline soils and increased to 86% in 2011. The cotton yields were lower at lower matric potentials, consistent with earlier results for other crops in the saline soils of Ningxia (Tan and Kang, 2009).

5. Conclusion

The SMP thresholds affected the extent of leaching of salts significantly. During the growth period of cotton, soil EC_e and SAR value decreased gradually in each soil layer, although the level of salt rose again in spring and winter. However, soil in the root zone (the first two layers, namely 0–0.2 m and 0.2–0.4 m) continued to be low in salt. After three years of irrigation, maximum leaching was observed at the SMP of −5 kPa. A combination of ridge planting, mulching, and drip irrigation to regulate the level of soil moisture and salt in saline soils with high EC_e and SAR achieved the desired effects in the form of higher germination percentage, greater reproductive growth, and increased yield. The higher the SMP, the more extensive the leaching and the better was the growth of cotton. Maximum yields were obtained at the SMP of −5 kPa, being 69% and 86% of the yields from non-saline soil over 2 and 3 years, respectively. The decrease of cotton yield was mainly due to the reduction of germination rate in Xinjiang region. By examining the extent of leaching layer by layer and its effect on the growth and yield of cotton, the lower limit of −5 kPa for the SMP at 0.2 m below the dripper can serve as a guide for irrigating the land in the first three years before sowing cotton during the reclamation of saline wasteland of Xinjiang, China.

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