Effects of different drip irrigation regimes on saline–sodic soil nutrients and cotton yield in an arid region of Northwest China

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ABSTRACT

A field experiment was conducted on a saline wasteland in Xinjiang, Northwest China, during 2008–2010 to evaluate the nutrient behavior and cotton yield during reclamation, applied by different drip irrigation regimes. The experiment included five treatments in which the soil matric potential (SMP) thresholds at 20 cm depth were controlled at -5 , -10 , -15 , -20 and -25 kPa. The results indicated that both soil salinity and sodicity declined significantly at 0–40 cm depth and greater reductions were achieved at higher SMP thresholds (-5 and -10 kPa) than in other treatments. The distributions in soil inorganic nitrogen (N) and available phosphorus (P) and potassium (K) in the soil profile were mainly influenced by the point-source characteristic of drip irrigation, drip irrigation regime and fertilization mode. With the reclamation of both soil chemical and physical properties, there were dramatic increases in soil N, P and K concentration by the end of 2010. The soil nutrient concentrations in N, P and K were all proportional to the SMP thresholds, as higher SMP could result in greater reductions in soil salinity and sodicity. Since crop growth became more vigorous during reclamation, there was also a considerable increase (9.7–31.9%) in soil organic carbon by the end of 2010, and the concentrations were also proportional to SMP thresholds. The highest cotton yield was obtained in S1 (-5 kPa) treatment for both 2009 (2.87 Mg ha^{-1}) and 2010 (3.60 Mg ha^{-1}). Additionally, the soil C:N ratios were inversely proportional to the SMP thresholds in 2009 and 2010. Considering the soil reclamation efficiency, soil nutrient stocks and cotton yield, SMP thresholds of -5 and -10 kPa could be used as effective measures to trigger irrigation in the first 3 years of saline–sodic soil reclamation in Xinjiang, Northwest China.

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1. Introduction

Soil salinity and sodicity, and their combination, are worldwide problems posing significant threats to the sustainable development of agriculture, especially in arid and semiarid regions (Oster et al., 1996; Qadir et al., 1997; Ma et al., 2012). In Xinjiang, a typical arid region of Northwest China, there are approximately 1.1×10^7 ha of saline wasteland, of which 7.27×10^6 ha are overly saline–sodic soils (Xi et al., 2005). Salinization and sodification of soils are serious land degradation issues in Xinjiang, where it is estimated that one-third of the arable land is affected by salinity and sodicity, which greatly reduces agricultural output in the area (Chen et al., 2010).

Under saline conditions, the reduced growth of crops is mainly attributed to the osmotic effect, which can reduce soil water

potential and nutrient availability and uptake by plants (Al-Karaki, 1997; Elgharably, 2011). Sodicity increases clay dispersion and reduces aggregate stability, which results in declining air permeability, infiltration and hydraulic conductivity (Wong et al., 2010). This can seriously hinder root respiration, hence reducing plant growth and activity of soil organisms. However, the typical inland arid conditions and water resource shortages in Xinjiang increase the difficulty of reclaiming saline–sodic soil.

Drip irrigation with its characteristic of applying water at low discharge rate and high frequency over a long period of time can maintain constant and high soil water potential in the root zone and reduce salinity levels in soil water by leaching, particularly near the drip emitters (Keller and Bliesner, 1990; Wang et al., 2011). Among all the factors, drip irrigation scheduling is the most important in salt leaching efficiency. Previous studies have evaluated the impact of different levels of soil matric potential (SMP) to trigger drip irrigation in arid and semiarid regions (Dou et al., 2011; Sun et al., 2012; Wan et al., 2012; Wang et al., 2012). These studies have

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mainly focussed on soil salinity, sodicity and soil hydraulic properties, particularly with regard to soil salt movement and plant health. However, very few studies have explored soil nutrients during the reclamation process under drip irrigation, and hence understanding of nutrients in saline-sodic soil under drip irrigation is limited.

Soil structure and root activity decline with increasing sodicity in a saline-sodic soil, thus reducing nutrient mobilities and leading to nutrient deficiencies (Wong et al., 2010). Therefore, organic matter and mineral nutrients in saline-sodic soils are generally at low levels. Nutrient behavior in saline-sodic soils during the reclamation process needs to be evaluated because of the changes in soil chemical composition during and after reclamation. Especially under conditions of drip irrigation with mineral fertilizer input, the variations of soil nutrients during reclamation remain largely unknown.

The objectives of this study were (1) to investigate the effects of drip irrigation triggered by different SMP thresholds on distribution of soil mineral nutrients (inorganic N, available P and K); (2) to ascertain variation in soil organic carbon (SOC) and (3) to measure the effects of different SMP thresholds on soil carbon-to-nitrogen (C:N) ratio and seed cotton yield during 3 years of reclamation under drip irrigation.

2. Materials and methods

2.1. Experimental site

The field experiments were conducted during 2008–2010 on a saline wasteland at Karamay farm (latitude: 45°22'N and longitude: 84°50'E, 350 m a.s.l.), which is located in the middle of the Jungger Basin in the Xinjiang Province, Northwest China. The area has a typical inland arid climate with annual precipitation of about 105 mm, mainly concentrated in June–August, and average annual evaporation capacity and temperature of about 3545 mm and 8.0 °C, respectively (Wang et al., 2007). The average depth to groundwater is about 2.5–3.0 m, and the electrical conductivity of the groundwater (EC_{gw}) ranged between 30 and 52 dS m⁻¹. Irrigation water is pumped from the reservoir in the west suburbs of Karamay, with EC_{iw} of 0.3 dS m⁻¹. The soils in the area are chloride-sulfate-type saline-sodic soils, which are typically in Xinjiang (Wang et al., 1993; Xi et al., 2005). The climate and special geographical conditions make this region liable to accumulate salt on the soil surface. The EC_e (electrical conductivity of saturated paste) and the nutrient concentration of soil samples at different soil depths are reported in Tables 1 and 2.

2.2. Plot layout and irrigation water management

The experiment included five water treatments (S1–S5) based on the SMP, measured with tensiometers located at a depth of 20 cm beneath a dripper near the center of the plot for each treatment (Fig. 1), that determined when to irrigate or to trigger irrigation. The SMP thresholds that triggered irrigation were –5 (S1), –10 (S2), –15 (S3), –20 (S4) and –25 kPa (S5). These treatments were replicated three times in a completely randomized block design. Plots consisted of 20 rows of cotton planted on 10 raised (15 cm) beds during 2008–2010, spaced at 0.8 m. The beds were mulched with white polyethylene sheets after sowing. Each bed was 0.4 m wide and 3.8 m long (Fig. 1). The size of plots was 8.0 m × 3.8 m. The location of water treatments was the same during the 3 years of the experiments.

Each treatment was irrigated with an independent irrigation system. The system consisted of a water tank (1000 L) and 30 drip tubes (10 tubes per plot). A tank filled with irrigation water was placed at 1 m above the ground to maintain water pressure in the

Fig. 1. Dimensions of beds and position of the tensiometer and soil sampling.

irrigation system within the range of 10–20 kPa. The drip tubes with 20 cm emitter intervals were placed at the center of each raised bed. To enable seedlings to emerge, 40 mm of water was applied to all treatments immediately after seeding. Cotton seedlings were thinned to the spacing described below, and irrigation treatments were initiated on 15 June (16 days after seeding), 2 June (23 days after seeding) and 5 June (26 days after seeding) in 2008, 2009 and 2010, respectively. Thereafter, 9.8 mm of water was applied when SMP reached the target values. The tensiometers were observed three times daily: 8:00, 12:00 and 18:00 h.

2.3. Plant and fertilizer management

Seeds of cotton were sown on 30 May 2008, 10 May 2009 and 8 May 2010 in double rows. The rows were 30 cm apart; within a row, the seeds were sown 10 cm apart. Soon after emergence, the plants were thinned to a spacing of 30 cm. Since the seeding date was relatively late in 2008, the emergence rate was low and the bolls did not grow well enough for harvest due to the low temperature in the late growing stages. Accordingly, there were no yield data for 2008. In 2009 and 2010, harvest was started on 2 October and 30 September and finished on 20 and 25 November, and the total harvest period lasted 49 and 57 days, respectively. The seed cotton was picked by hand at 4–7-day intervals, and the total weight per plot was checked at each harvest time.

Basal dose of 450 kg ha⁻¹ of a compound fertilizer (16% N, 35% P₂O₅ and 8% K₂O) was uniformly applied to the plots at the time of plowing before seeding in 2008–2010. This fertilizer dose was supplemented with urea (46% N), applied with the irrigation water; 0.15 L of an 11 mg kg⁻¹ urea solution was added to the irrigation tank every time irrigation was applied.

2.4. Soil sampling and chemistry analyses

In a saline soil, the soil salinity distributions clearly showed leaching near the drip lines, an area where the root density has been found to be maximum (Hanson et al., 2006; Hu et al., 2009). Since the low EC_e zones we found were usually within 40 cm (Wang et al., 2011), a soil depth interval of 0–40 cm was analyzed. Soil samples were obtained on soil cores from each plot with an auger (2.0 cm in diameter and 15 cm long) on 12 May 2008 (before seeding), 13 September 2008, 14 September 2009 and 13 September 2010 (after irrigation ended). The distances of sampling points to drip emitters were 0, 5, 10, 15, 20, 25, 30, 35 and 40 cm, and all sample depths were the same: 0–5, 5–10, 10–20, 20–30 and 30–40 cm (Fig. 1). All soil samples were air-dried and sieved through a 1 mm sieve.

The soluble salt estimates were based on extracts of saturated soil. The EC values were determined with a conductivity meter (DDS-11A, REX, Shanghai). Sodium adsorption ratio (SAR) was

Table 1Soil texture, bulk density, electrical conductivity of saturated paste extracts (EC_e) and SAR of the initial soil profile at Karamay, Xinjiang, Northwest China.

Soil depth (cm)	Soil mechanical composition (%)			Soil texture	Soil bulk density ($g\ cm^{-3}$)	EC_e ($dS\ m^{-1}$)	SAR
	Clay	Silt	Sand				
0–40	1.18	93.5	5.34	Silt	1.33	46.1	40.3
40–60	1.03	99.0	0.00	Silt	1.43	27.4	25.7
60–90	0.54	95.4	4.07	Silt	1.47	15.4	28.2
90–120	0.41	96.0	3.56	Silt	1.56	30.4	19.5
120–180	0.26	96.1	3.68	Silt	1.38	16.4	21.4

Table 2The concentration of total N, soil organic carbon (SOC), available P and K and inorganic N (NO_3^- -N and NH_4^+ -N) in the initial soil profile at Karamay, Xinjiang, Northwest China.

Soil depth (cm)	Total N (%)	SOC (%)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)	NO_3^- -N ($mg\ kg^{-1}$)	NH_4^+ -N ($mg\ kg^{-1}$)
0–30	0.03	0.33	4.06	115.4	8.4	18.7
30–60	0.02	0.27	2.44	119.5	10.6	9.9
60–90	0.02	0.26	1.83	132.0	10.3	10.8
90–120	0.01	0.21	2.23	82.4	11.1	9.9
120–180	0.02	0.14	0.81	70.1	11.5	9.0

calculated from the following equation using concentrations of the cations Na^+ , Ca^{2+} and Mg^{2+} in $mmol\ L^{-1}$:

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

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

Total nitrogen (TN) was determined using the micro-Kjeldahl method, with 2.0 g of soil being digested in H_2SO_4 and H_2O_2 solution before measurement (Stuart, 1936). The inorganic N (ammonium and nitrate: NH_4^+ and NO_3^-) was determined in $2\ mol\ L^{-1}$ KCl extract on a Skalar automatic analyzer (Bundy and Meisinger, 1994). Olsen P (available P) was extracted with $0.5\ mol\ L^{-1}$ $NaHCO_3$ at pH 8.5 and determined according to Olsen and Sommers (1982). Available potassium (K) was determined by flame photometer method using $1.0\ mol\ L^{-1}$ CH_3COONH_4 adjusted to pH 7.0 as the extractant. Soil organic carbon (SOC) was determined by high temperature combustion on a LECO CNS-2000 analyzer (Wong et al., 2008).

The values for soil organic carbon (SOC) and total nitrogen (TN) were used to calculate the carbon-to-nitrogen ratio, C:N.

2.5. Statistical analyses

Tukey's significant difference (TSD) was used to compare and rank the treatment means at $p < 0.05$ for the EC_e , SAR, TN, C:N ratio and cotton yield. Two factors, sampling date ($n = 6$) and treatment ($n = 5$), were included in the ANOVA for soil EC_e , SAR and nutrients. Statistical analyses were performed using SPSS (version 15.0) and Excel. Soil nutrient spatial distributions were mapped with Surfer 7.0.

3. Results and discussion

3.1. Weather and irrigation

The summer temperatures (July and August) in 2008 were higher than those in 2009 and 2010, while in other months, the mean temperatures were very similar among the 3 years (Fig. 2). Total rainfall during the experimental period was 70.8, 81.2 and 114.6 mm in 2008, 2009 and 2010, respectively, with correspondingly seven, six and nine effective rainfall ($>5\ mm$) events. There were four heavy rainfall events (rainfall intensity $> 16\ mm\ h^{-1}$) in early July 2008, which was twice as much as observed in 2009 and

2010. Comparatively, the temporal distribution of rainfall was more uniform in 2010 than in the other years (Fig. 2).

Before cotton emerged, all treatment plots were irrigated with the same amount of water to ensure uniform germination. After that, irrigations were triggered by different SMP thresholds. Higher SMP threshold resulted in more irrigation times and hence greater amounts of irrigation water (Table 3). The most irrigation water was applied in S1 ($-5\ kPa$) each year, while the maximum (665.6 mm) was in 2008.

3.2. Temporal changes of soil EC_e and SAR

The variation of soil EC_e and SAR after irrigation terminated in each year is shown in Fig. 3. During the irrigation season, salts moved downward with water, thus after the irrigation ceased in fall (September), the EC_e value significantly declined for each treatment compared with the initial values in 2008 before seeding (13 May) (Fig. 3a). Compared with the initial EC_e in 2008, the reduction in EC_e after 3 years at 0–40 cm depth varied from 56% (S5) to 89% (S1) for the five treatments. The reduction of EC_e decreased with the decreasing SMP threshold for each year. Thus more reclamation occurred in S1 ($-5\ kPa$) and S2 ($-10\ kPa$) than for the other treatments. By the end of the third cropping season, the EC_e for S1 and S2 treatments had reduced from 47.0 to 5.3 and 8.1 $dS\ m^{-1}$, respectively, which are in the range of threshold salinity of 7.7 $dS\ m^{-1}$ for cotton (Maas and Hoffman, 1977). This could only occur if more

Fig. 2. The monthly rainfall and mean temperature during experimental stages in each year. 2008-C, 2009-C and 2010-C, monthly cumulative rainfall in 2008, 2009 and 2010, respectively; 2008-M, 2009-M and 2010-M, monthly mean temperature in 2008, 2009 and 2010, respectively.

Table 3

Irrigation and amount of applied water for each treatment during the experimental stages in 2008, 2009 and 2010.

Years	Treatments	Fresh water for seedlings (mm)	During treatment	
			Irrigation times	Water depth (mm)
2008	S1 (–5 kPa)	40	68	666
	S2 (–10 kPa)	40	47	460
	S3 (–15 kPa)	40	30	293
	S4 (–20 kPa)	40	28	274
	S5 (–25 kPa)	40	26	254
2009	S1 (–5 kPa)	40	65	636
	S2 (–10 kPa)	40	47	460
	S3 (–15 kPa)	40	38	372
	S4 (–20 kPa)	40	37	362
	S5 (–25 kPa)	40	25	244
2010	S1 (–5 kPa)	40	65	627
	S2 (–10 kPa)	40	56	541
	S3 (–15 kPa)	40	38	363
	S4 (–20 kPa)	40	28	274
	S5 (–25 kPa)	40	24	235

water was applied to the soil than was used by the crop within this depth, thus causing leaching.

The changes in SAR with time (Fig. 3b) were similar to those of EC_e . There were considerable reductions of SAR at 0–40 cm depth. After the third irrigation season, the declines in SAR, relative to the initial level, were 76, 60, 52, 46 and 41% for S1–S5 treatments, respectively (Fig. 3b). In the fall, the reduction of SAR at 0–40 cm soil depth also decreased with the decreasing SMP threshold. The reductions in SAR could be enhanced in calcareous soil under cropped conditions, because plant roots can affect the soil chemical environment by increasing the partial pressure of carbon dioxide (CO_2), which will facilitate the dissolution of calcite, thereby providing a source of Ca to replace exchangeable Na (Qadir et al., 2002). This process is more efficient in cropped than in uncropped soils as plant roots can exert higher CO_2 partial pressure (Robbins, 1986a,b; Qadir et al., 2002, 2007). Apart from root action, the decrease in SAR can also be attributed to Ca^{2+} supplied in irrigation water and lime dissolution through soil microbial activity (Qadir et al., 1997).

3.3. Spatial and temporal changes in soil nutrients

3.3.1. Soil N

In this study, soil inorganic N (NO_3^- -N and NH_4^+ -N) distribution within 40 cm depth was analyzed after irrigation ceased for each treatment in 2010. The two types of inorganic N accumulated mainly in the upper soil layer (0–20 cm) (Fig. 4). The NO_3^- -N and

NH_4^+ -N formed a concentration gradient with soil depth, with the highest values concentrated around the drip emitter. This may be due to the point-source characteristic of drip irrigation and the fertilization mode. Under point-source infiltration, water can form a wetting area in close proximity to a dripper (Chen et al., 2009); hence, the nutrient dissolved in and moving with irrigation water can form a similar shape to the wetting area in the soil profile. Compared with the initial value (Table 2), there were dramatic rises in both the NO_3^- -N and NH_4^+ -N in the soil profile for each treatment after 3 years of the experiment. There are two main reasons for this: applied fertilizer and crop roots. Applying N fertilizer, on the whole, can increase the inorganic N concentration and therefore the NO_3^- -N and NH_4^+ -N stocks in the soil profile (Yin et al., 2007). Additionally, soil reclamation was more efficient at higher SMP thresholds (Fig. 3), and thus more roots distributed in soil for S1 (–5 kPa) and S2 (–10 kPa) treatments could promote adsorption, transportation and biometabolic action of ionic species in soil, which results in accumulation of nutrients (Ma et al., 2012). This can also explain why more NO_3^- -N and NH_4^+ -N accumulated at higher SMP thresholds after the experiment ended in 2010 (Fig. 4).

After the first growing season, there was a significant increase in total N in the upper 40 cm of soil in all treatments, compared with those before seeding (Fig. 5); the increase rates in the range of 8.4–38.9% were proportional to the SMP thresholds. In the following 2 years, the total N for each treatment steadily increased.

Fig. 3. The average electrical conductivity of saturated soil extract (EC_e (a)) and sodium adsorption ratio (SAR (b)) values at 0–40 cm depth before seeding in 2008 and after irrigation terminated in 2008, 2009 and 2010 for each treatment. Tukey's significant differences (TSDs, $p \leq 0.05$) for EC_e were 1.39 and 1.42 $dS m^{-1}$ among the treatments and dates, respectively, while for SAR, the TSDs ($p \leq 0.05$) were 2.89 and 2.92 among the treatments and dates, respectively.

Fig. 4. The spatial distribution of soil inorganic nitrogen in nitrate (NO_3^- -N) and ammonium (NH_4^+ -N) in the vertical transect perpendicular to the drip tubes for each treatment after irrigation ceased in 2010.

Compared with the initial value, the total N increased by 79.5, 69.4, 43.3, 52.8 and 35.6% for S1–S5 treatments, respectively, after the experiment ended in 2010. The considerable increase in soil N was mainly due to the soil reclamation and fertilizer application. During reclamation, both the aboveground and underground parts of the crop can flourish yearly, and large amounts of tiny holes and channels observable in the soil with growing crops indicate a fibrous root system, creating micropores in the soil (Hayashi et al., 2006; Tejada et al., 2006). This can improve hydraulic conductivity in the soil structure and provide available water and nutrients for crops to grow. However, the biologically fixed N through the crop roots, the shedding of older leaves and the dead plants may also have increased the organic matter and N content in the upper 40 cm of soil (Qadir et al., 1997).

Fig. 5. The total nitrogen (TN) content at 0–40 cm depth before seeding in 2008 and after irrigation terminated in 2008, 2009 and 2010 for each treatment. The Tukey's significant differences (TSDs) ($p \leq 0.05$) for TN were 0.0015 and 0.0017% among the treatments and dates, respectively.

3.3.2. Soil available P

The soil available P distributions in the soil profile (Fig. 6) were similar to those for soil inorganic N (Fig. 4). By the end of 2010, the average value of soil available P in 0–40 cm depth had increased to 11.1–6.8 mg kg^{-1} for S1–S5 treatment. Most soil available P accumulated in the upper soil layer (0–20 cm), which might be mainly due to the point-source characteristic of drip irrigation and P-containing fertilizer. In addition, more CaCO_3 present at shallower soil depths may have absorbed more P than in deeper soil layers (Wang et al., 2011, 2012). Soil moisture content influences the effectiveness and availability of applied P (Campo et al., 1998); moreover, the higher water availability in the topsoil under drip irrigation could be related to a higher transformation from organic to available P (Yang et al., 2011). This can explain the phenomenon of available P content in the soil profile being higher in S1 and S2 than in the other treatments (Fig. 6). For S1 and S2 treatments, there was more available P concentrated in deeper soil layers (30–40 cm) under drip emitters than in other treatments. This might be caused by the large amount of applied water, which could leach soil P to deeper layers.

In the cropped treatments, the mineral weathering of apatite, dissolution of slightly soluble P compounds and mineralization of some organic P are believed to be the factors responsible for increased soil P content (Qadir et al., 1997; Havlin et al., 2005; Chai et al., 2014). Irrigation method can alter soil properties, thus affecting the transformation and movement of soil nutrients and so affecting soil P content (Yang et al., 2011), which can also explain the changes of soil P content under drip irrigation in the present study.

3.3.3. Soil available K

After 3 years of the experiment, the soil had available K in the range of 155–179 mg kg^{-1} in 0–40 cm depth of soil for the five treatments (Fig. 7). By the end of the experiment, the soil available K had increased by 55.1, 36.5, 32.5, 34.8 and 45.4% for S1–S5 treatments, compared with the initial value, respectively. The increase in soil available K was mainly due to the release of K from illite and applied fertilizer. Like many soils in the area, the soil in this study had illite as the dominant clay mineral (Cheng and Fukuhara, 1994; Guan

Fig. 6. The spatial distribution of available soil P in the vertical transect perpendicular to the drip tubes for each treatment after irrigation ceased in 2010.

Fig. 7. The spatial distribution of available soil K in the vertical transect perpendicular to the drip tubes for each treatment after irrigation ceased in 2010.

et al., 2011), which serves as a good reservoir of plant-available K. The shallower samples had slightly lower concentrations of K, which was similar to those for soil N and P (Fig. 7).

3.3.4. SOC

In saline-sodic soil, the effects of salinity and sodicity on plant health adversely impact on SOC stocks, generally leading to less SOC (Wong et al., 2010). Comparing with the initial value, there were significant increases in SOC for S1–S3 treatments after the first irrigation season (13 September 2008), and the increase rates from S3 to S1 were in the range of 5.3–17.4% (Fig. 8). For S4

and S5 treatments, the increase rates were not statistically significant. This was mainly due to the more vigorous cotton growth in the S1–S3 than in the other treatments, as soil reclamation was more efficient at higher SMP thresholds (Fig. 3). In the second irrigation season, there was a constant increase in SOC for all treatments, and the highest increase rate of 8.3% was for the S1 treatment compared with that in the first year (13 September 2008). The presence of plants can increase the SOC in several ways (Jinbo et al., 2006). In the present study, the plant residue after harvest was incorporated into the soil before plowing in the next spring, which was an important factor leading to the consistent increase in SOC each year. Comparing with the initial value, SOC increased by 31.9, 24.2, 18.5, 14.0 and 9.7% for S1–S5 treatments, respectively, when the experiment ended in 2010. In highly saline-sodic soils, enhanced SOC loss can occur through dispersion of aggregates on wetting, which increases substrate accessibility and availability to the soil microbial biomass (Oades, 1984). At higher SMP thresholds, soil reclamation was more efficient both for nutrients and for structure, which could explain the differences among the five treatments in SOC each year (Fig. 8).

3.4. Cotton yield and soil carbon-to-nitrogen (C:N) ratio

As shown in Table 4, the highest seed cotton yields for both 2009 (2.87 Mg ha⁻¹) and 2010 (3.60 Mg ha⁻¹) were obtained in S1 treatment, for which the yields were 67 and 84% of the average level for non-saline soil in this region, respectively. Statistical analysis showed that maintaining different SMP values during the growing season had a significant effect on seed cotton yield in both 2009 and 2010. The yields of the five treatments in 2010 were 8–42% greater than those in 2009. Moreover, the seed cotton yield increased as the SMP thresholds increased, which is in agreement with the results

Fig. 8. The content of soil organic carbon (SOC) at 0–40 cm depth before seeding in 2008 and after irrigation terminated in 2008, 2009 and 2010 for each treatment. The Tukey's significant differences (TSDs) ($p \leq 0.05$) for SOC were 0.03 and 0.05% among the treatments and dates, respectively.

Table 4

Seed cotton yield and soil carbon-to-nitrogen (C:N) ratio for each treatment in 2009 and 2010.

Years	Treatment	Seed cotton yield (Mg ha ⁻¹)	C:N
2009	S1 (–5 kPa)	2.9 ^a	23.2 ^b
	S2 (–10 kPa)	2.2 ^{a,b}	23.3 ^b
	S3 (–15 kPa)	1.9 ^{a,b}	23.7 ^{a,b}
	S4 (–20 kPa)	2.2 ^{a,b}	25.0 ^{a,b}
	S5 (–25 kPa)	1.2 ^b	27.2 ^a
2010	S1 (–5 kPa)	3.6 ^a	21.5 ^c
	S2 (–10 kPa)	2.4 ^b	21.5 ^c
	S3 (–15 kPa)	2.2 ^{a,b}	22.0 ^c
	S4 (–20 kPa)	2.3 ^b	22.7 ^b
	S5 (–25 kPa)	1.8 ^c	23.6 ^a

Values for each separate year in a column followed by the same letter are not significantly different at $p \leq 0.05$.

Fig. 9. The relationship between seed cotton yield and soil carbon-to-nitrogen (C:N) ratio for the combined data of 2009 and 2010.

of a study conducted by Jiao et al. (2006) and Wan et al. (2012) in Ningxia, Northwest China.

Soil carbon-to-nitrogen (C:N) ratio is one of the key factors influencing soil organic matter (SOM) decomposition (Cong et al., 2012). Relatively high C:N ratio (>30) can result in the competition for nitrogen and adverse impact on crop yields (We et al., 2011). In this study, the ratios were significantly influenced by SMP thresholds and were inversely proportional to the SMP thresholds both in 2009 and in 2010 (Table 4). Compared with those in 2009, the ratios in 2010 decreased by 7.4, 7.7, 6.9, 9.4 and 13.4% for S1, S2, S3, S4 and S5 treatments, respectively.

In crop land, the SOC pool is dependent on inputs from vegetation (Wong et al., 2010). Moreover, soil TN change is generally assumed to follow SOC dynamics because both elements are bound into organic compounds (Cong et al., 2012). In saline-sodic soil, the sum of the osmotic and matric stresses limited crop yields, the amount of applied N, P and K taken up by the crop and the amount of C produced by the crop in the form of roots and foliage. Apparently, in regard to the C:N ratio, the limitation on N uptake was greater than that on the production of C (Table 4). In high SMP threshold (–5 kPa) treatment, more soil reclamation occurred, which resulted in vigorous plant growth and more soil microorganism quantity (Batra and Manna, 1997). This can lead to the increasing rates of SOC consumption as well as the soil TN accumulation. Therefore, of all treatments, TN was the highest and SOC was the lowest for the S1 treatment. Consequently, for the combined data of 2009 and 2010, C:N ratio decreased with increasing cotton yield, and a logarithmic function relationship was found between them (Fig. 9).

4. Conclusions

The soil salinity, sodicity and nutrients were significantly affected by the SMP thresholds under drip irrigation during the 3 years of reclamation. There were larger reductions of EC_e and SAR in S1 (–5 kPa) and S2 (–10 kPa) than in the other treatments at 0–40 cm soil depth. The distributions of soil inorganic N and available P and K in the soil profile were mainly influenced by the point-source characteristic of drip irrigation, drip irrigation regime and fertilization mode. With the reclamation in both soil chemical and physical properties, there were dramatic increases in soil N, P and K concentration by the end of 3 years of the experiment. The soil concentration of inorganic and total N, available P and K were proportional to the SMP thresholds, as higher SMP resulted in more efficient soil reclamation. Since cotton growth became more vigorous during reclamation, there was also a considerable increase (9.7–31.9%) in SOC by the end of 2010, and the increased rates were proportional to SMP thresholds. The highest cotton yield was obtained in S1 (–5 kPa) treatment for both 2009 (2.87 Mg ha⁻¹) and 2010 (3.60 Mg ha⁻¹). The soil C:N ratios were inversely proportional to the SMP thresholds in 2009 and 2010. Overall, considering the soil reclamation efficiency, soil nutrient stocks and cotton yield, SMP thresholds of –5 and –10 kPa could be used as effective measures to trigger irrigation in the first 3 years of saline-sodic soil reclamation in Xinjiang, Northwest China.

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