

Improvements of soil salt characteristics and nutrient status in an impermeable saline–sodic soil reclaimed with an improved drip irrigation while ridge planting *Lycium barbarum* L.

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Abstract

Purpose Takyric solonetz is spread widely across the arid area of northwest China. The extremely poor soil structure and low hydraulic conductivity ($K_s < 0.1 \text{ mm day}^{-1}$) hinder its amelioration. The purpose of this study was to investigate the soil salt leaching characteristics, nutrient contents, and distributions in the impermeable saline–sodic soil reclaimed with an improved drip irrigation method, and to explore the impacting mechanisms of agronomic practices involved on the amelioration.

Materials and methods A 3-year field experiment was conducted to investigate the success of planting *Lycium barbarum* L. in the highly saline–sodic wasteland of takyric solonetz using drip irrigation. The soil beneath the drip emitters near the plants was replaced with sand in niches that were 0.2 m in ground diameter and 0.2 m deep. Five treatments based on soil matric potential (SMP) were designed to find the optimal irrigation schedule: -5 kPa (S1), -10 kPa (S2), -15 kPa (S3), -20 kPa (S4), and -25 kPa (S5).

Results and discussion A significant improvement was found in soil infiltration capability, which was demonstrated by the increasingly enlarged wetted area beneath the drip emitter. This improvement was resulting from the combined affects of all the agronomic practices involved, including drip irrigation, sand-filled niches, film mulching. After 3 years, soil salt leaching rates in S1–S5 root zones were 68.16, 39.45, 26.56, 25.14 and 10.40%, respectively, indicating that the higher SMP improved soil salt leaching. The increased soil EC_e /SAR ratio reflected the amelioration of soil physical properties. After planting, the soil nutrient status considerably improved. N fertilizer, which often was leached away, should be applied in the latter half of an irrigation event. Available P content in the soil was relatively low and it was necessary to apply adequate P fertilizer to meet crop growth needs, while the studied soil was rich in K and moderate supplement of K fertilizer was proposed. After 3 years, S2, S3, and S4 produced the significantly higher dry fruit yields ($\sim 900 \text{ kg ha}^{-1}$), which were close to those produced by local farmland. **Conclusions** Our findings indicated that an improved drip irrigation made the reclamation of an impermeable saline–sodic soil possible. The key operations included drip irrigation, sand-filled niches beneath drip emitters, ridge tillage, film mulching, and the use of thresholds to control SMP.

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Keywords Drip irrigation · Saline–sodic soil · Salt leaching · Soil infiltration · Soil matric potential

Abbreviations

BD Soil bulk density
 EC_e Electrical conductivity of saturated paste extract
ESP Exchangeable sodium percentage

OC	Soil organic carbon
pH _s	pH of saturated paste
SAR	Sodium adsorption ratio of saturated paste extract
SMP	Soil matric potential
TN	Soil total nitrogen
TP	Soil total phosphorous

1 Introduction

Salt-affected soil is one of the most important abiotic stresses that limit crop production around the world (Nan et al. 2016), particularly in arid and semiarid regions. Saline–sodic and sodic soils account for 60% of all the salt-affected soils across the globe (Qadir et al. 2000). They are more difficult to reclaim than saline soils, because of their poor structure and low permeability (Oster and Jayawardane 1998; Qadir et al. 2001; Li 2006), which leads to a decrease in water and air movement, plant-available water, root penetration, and plant establishment (Akhter et al. 2004; Li et al. 2016).

Takyric solonetz is a highly saline–sodic soil (IUSS Working Group WRB 2007) and is the prominent soil type in the arid area of northwest China. The soils have excessively high sodium levels, a general ESP (exchangeable sodium percentage) of 15–60 that can reach >90 at some locations, and a pH of 9–10, which leads to soil structure deterioration and very low hydraulic conductivity ($K_s < 0.1 \text{ mm day}^{-1}$). The soil does not support any vegetation except some blue–green algae, such as *Microcoleus* that grows in patches during the monsoon season. In recent decades, many methods have been attempted to reclaim this soil. They included deep plowing, organic fertilizer application, rice cropping along with frequent irrigation and drainage, replacement of the entire surface soil with a good soil, and the use of chemical amendments (Comprehensive Exploration Team 1963; Yin 1985; Wang et al. 1993; Wang et al. 2010). However, most methods were not effective because of the low K_s of the soils. Furthermore, deep plowing and rice cropping were unable to ameliorate this soil over the long term (Comprehensive Exploration Team 1963; Wang et al. 1990). Occasionally, chemical amendments, including gypsum, sulfuric acid aluminum sulfate, and calcium chloride, have effectively ameliorated soil sodicity (Qadir et al. 2001). However, the use of these chemical amendments is too costly and is of only marginal economic interest to local farmers. Therefore, a large area of the takyric solonetz wasteland in northwest China has not been reclaimed to date. With the expanding population and the loss of cropland due to rapid urbanization, the need to reclaim this impermeable saline–sodic soil properly, effectively, and at a low cost is becoming urgent.

Drip irrigation, which is characterized by the point source diffusion properties of high frequency and small flow, is less destructive to the soil structure than surface irrigation (Hanson

et al. 2009). It can lead to adequate soil water, nutrients, and aeration in the root zone through the precise application of water and nutrients (Batchelor et al. 1996; Ayars et al. 1999). Furthermore, it has a higher salt-leaching efficiency than other irrigation techniques, which means that it has been widely used to reclaim salt-affected soils (Burt and Isbell 2005; Rajak et al. 2006). Through maintaining constant and high soil water contents in root zone, drip irrigation can reduce soil salinity, particularly near the drip emitters and, meanwhile, reduce deep percolation (Hou et al. 2009; Wang et al. 2012). During drip irrigation, soil salts tend to move with water to the fringes of the wetted area, resulting in the decreased osmotic potential in root zone which reduces the osmotic stress on plant growth (Wang et al. 2011; Zhang et al. 2013). Moreover, reclamation of saline–sodic soils under cropped conditions can facilitate reclamation due to the enhanced dissolution of calcite within the rootzone which provides a source of calcium to replace exchangeable sodium (Qadir et al. 1997, 2001). Reclamation under cropped conditions also poses the possibility of providing an economic return from the crop yield. In recent years, a number of water and salt regulation schemes based on the drip irrigation of various salt-affected soils have been established, and they have considerably improved soil properties and productivity (Wang et al. 2011; Wan et al. 2012; Sun et al. 2013; Li et al. 2015; Li et al. 2016). However, most were implemented in saline soils or saline–sodic soils with acceptable soil permeability, and there has been little research into drip irrigation performance in a strongly saline–sodic soil with extremely low permeability. The traditional methods are ineffective, time consuming, and expensive, but if takyric solonetz could be reclaimed through single drip irrigation, with some improved supporting measures and without any additional chemical amendments, the lower reclamation cost could benefit local farm incomes by raising local agricultural productivity, and it could also improve environmental protection by increasing vegetation cover. Furthermore, it could provide a new reclamation method for saline–sodic and sodic soils with low permeability that could be used in other parts of the world. Hence, a 3-year field experiment was conducted, and the results proved that the reclamation of takyric solonetz was achieved while ridge planting *Lycium barbarum* L. with an improved drip irrigation method. The method mainly involves applying water to a sand-filled niche beneath drip emitter before its infiltration into the native soil. The water and salt distribution under different water treatments was studied, and the drip irrigation schedule based on controlling soil matric potential was proposed (Zhang et al. 2013). However, more soil properties, such as soil salt leaching, physical properties, and nutrient status, need to be explored to explain the mechanism of soil reclamation. The hypothesis of this study was that the salt components and the nutrient contents in saline–sodic soil would be changed along with salt leaching during

reclamation. So, based on the previous studies, this study aimed to investigate the soil salt leaching characteristics (partly related to the soil physical properties), nutrient contents, and distributions in takyric solonetz reclaimed with an improved drip irrigation method mentioned above and to discuss the impacting mechanisms of the agronomic practices involved on its amelioration. The final aim was to identify an efficient, rapid, and low-cost method that could be used to reclaim the impermeable saline–sodic soil.

2 Materials and methods

2.1 Experimental site

The experimental site was located in the Xidatan area (38° 47′–38° 57′ N, 106° 20′–106° 30′ E, altitude 1095 m) of Pingluo County, Ningxia Hui Autonomous Region, northwest China. The station has a typical arid continental climate, with a mean annual temperature of 9.4 °C and a mean annual precipitation of 178 mm. The mean annual potential evaporation is >2000 mm. The soil is classified as takyric solonetz (IUSS Working Group WRB 2007), and Xidatan is its typical distribution area in China, with the area of more than 2×10^4 ha. The local soil environment is extremely poor due to the lack of vegetation. The water table at the experimental site is about 2.5 m belowground, and ground water mineralization is generally $<3 \text{ g L}^{-1}$. There is little interannual variation in the water table and ground water salinity, which indicates that the ground water does not participate in soil formation. This is probably due to the impermeability of takyric solonetz (Wang et al. 1993).

The typical arid climate and geographical conditions result in the high salinity and sodicity of the surface soils. At 0–30 cm depth (Table 1), the average electrical conductivity of saturated paste extract (EC_e), pH of saturated paste (pH_s), and sodium adsorption ratio of saturated paste extract (SAR) were 12.3 dS m^{-1} , 9.4 and $44.1 (\text{mmol L}^{-1})^{0.5}$, respectively. The saturated hydraulic conductivity of the soil is very low ($K_s < 0.01 \text{ mm day}^{-1}$), especially when irrigated with non-saline water which results in soil dispersion and clogging of the soil pores (Quirk and Schofield 1955; Tedeschi and Dell’Aquila 2005; Basile et al. 2012). The detailed properties of the studied soil are shown in Tables 1 and 2.

2.2 Experimental design

2.2.1 Agronomic practices

The preparation of the native soil included deep plowing to a depth of 0.5 m. Then, beds were constructed that were 0.5 m in height, 1 m in width, and with a distance of 3 m between bed centers (Fig. 1a). Drip irrigation lines, with an emitter

spacing of 0.2 m and a flow rate of 0.76 L h^{-1} at an operating pressure of 0.03 MPa, were placed along the center line of each raised bed. Irrigation water, at the salinity shown in Table 3, was obtained from a reservoir near the experimental field.

After constructing the beds, semiellipsoid pits, with a volume of about 4.2 L, a ground surface diameter of 0.2 m, and a depth of 0.2 m, were dug beneath the emitters, where *L. barbarum* L. seedlings were to be planted (Fig. 1a) and filled with sand. On 25 April 2009, *L. barbarum* L. (the fruit is also known as wolfberry, cultivars: Ningqi no. 1) seedlings were transplanted into the center of the beds at intervals of 1 m where the sand-filled niches were located. The beds were then mulched with white polyethylene film (Fig. 1a, c).

A drainage ditch (0.5 m wide and 0.5 m deep) was dug around the field to minimize temporary waterlogging and associated soil saturation in the experimental plots. The beds, irrigation system, plants, and drainage ditches remained unchanged during the 3-year experiment.

2.2.2 Plot layout and irrigation treatments

The experiment included five water treatments based on soil matric potential (SMP), which was measured with tensiometers that had been buried to 0.2 m depth beneath the drip emitter (Fig. 1a, c). The SMP threshold values used to trigger irrigation were -5 kPa (S1), -10 kPa (S2), -15 kPa (S3), -20 kPa (S4), and -25 kPa (S5). The treatments were replicated three times ($3 \times 5 = 15$ plots) and were laid out using a completely randomized block design. Each $12 \text{ m} \times 12 \text{ m}$ plot consisted of four raised beds, and each treatment had an independent drip irrigation system consisting of valves, pressure gauges, a flow meter, a screen filter, a fertilizer tank, and 12 drip lines (4 lines/plot).

Immediately after transplanting the *L. barbarum* L. seedlings, 20 mm of water was applied over a period of 3 days beginning 26 April 2009 to reduce soil salinity near the plant and to provide favorable soil moisture levels for seedling survival. Thereafter, based on previous experience with plant establishment in other salt-affected soils northwest China (Jiao et al. 2008; Tan and Kang 2009; Wan et al. 2012) and on field observation of water infiltration and plant growth on-site, all treatment plots were irrigated uniformly by controlling the SMP levels above -10 kPa to ensure uniform survival and growth during the initial growth stage. Water treatments based on the different SMP threshold values were initiated on 28 August 2009. At each application in the first year, 5 mm of water was applied when the SMP reached the designated threshold. In the following 2 years, 10 mm of water was applied at the beginning of the growing seasons (20 April 2010 and 14 April 2011) to leach the salts brought nearer the surface during winter because of the lack of irrigation and the upward water movement due to the freeze–thaw cycle and direct

Table 1 Soil main physicochemical properties in the initial soil profile

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Soil texture	BD (g cm ⁻³)	EC _e (dS m ⁻¹)	pH _s	SAR (mmol L ⁻¹) ^{0.5}	EC _e /SAR ratio
0–10	1.35	90.59	8.06	Silt	1.44	18.54	8.90	39.76	0.47
10–20	0.99	95.93	3.08	Silt	1.53	11.66	9.58	54.01	0.22
20–30	0.85	95.75	3.40	Silt	1.59	6.69	9.52	38.59	0.17
30–40	1.02	92.32	6.66	Silt	1.64	4.16	9.51	23.15	0.18
40–60	0.86	86.12	13.02	Silt	1.60	2.45	9.50	15.43	0.16
60–80	0.43	78.65	20.92	Silt loam	1.63	1.89	9.43	7.72	0.24
80–100	0.26	71.90	27.84	Silt loam	1.55	1.67	9.24	7.72	0.22
100–120	0.7	83.0	16.3	Silt	1.60	1.50	9.18	7.72	0.19

BD bulk density, EC_e electrical conductivity of saturated paste extract, pH_s pH value of saturated paste, SAR sodium adsorption ratio of the saturated paste extract

evaporation of water to air from the soil surface. Thereafter, 5 mm of water was applied when the SMP reached the threshold value for each treatment. The irrigation rates are shown in Table 4.

2.2.3 Fertilization and field management

Urea, phosphoric acid, and potassium nitrate were added to the fertilizer tank and dissolved in water so that the fertilizer was applied with the irrigation water. The same amount of fertilizer was applied to the five treatments. Because *L. barbarum* L. is a perennial woody plants, with the increasing plant age, the fertilization rates increased year by year (except K₂O, which is rich in native soil). The accumulated totals of converted N, P₂O₅, and K₂O applied were 160, 100, and 75 kg ha⁻¹, respectively in 2009; 300, 150, and 100 kg ha⁻¹ in 2010; and 500, 240, and 50 kg ha⁻¹ in 2011 (Table 4).

Field management was similar to the practices followed on local and high-yielding farmlands and included pruning, trimming, weeding, and application of pesticides to control insects.

2.3 Soil sampling and analysis

Soil samples were obtained from each plot with an auger (diameter 4.0 cm; length 20 cm) at the locations shown in Fig. 1b, c. They were taken on 23 April 2009 (before transplanting the seedlings) and at the end of each growing season (28 October 2009, 18 October 2010, and 16 October 2011). The sampling location was as close to, but not in, the sand-filled niche to avoid sampling the sand-filled niche (Fig. 1c). The horizontal sampling distances from the drip lines were 0, 10, 20, 30, 40, 60, 80, 100, 120, and 150 cm; and the sampling depths were 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm (Fig. 1). The soil water content was determined gravimetrically on the field moist subsamples after carefully removing the surface organic materials and fine roots. Soil volumetric moisture content (SVMC) was calculated by multiplying the gravimetric water content by real-time soil bulk density. The remaining soil subsamples were air-dried and passed through a 1-mm sieve. Then, three replicates of the soil samples were combined into one sample to reduce the time taken to analyze the large number of samples. The chemical analysis was finished in 8 weeks after sampling.

Table 2 Soil nutrient concentrations in the initial soil profile

Soil depth (cm)	TN (g kg ⁻¹)	TP (g kg ⁻¹)	OC (g kg ⁻¹)	Available nutrients (mg kg ⁻¹)			
				NH ₄ ⁺ -N	NO ₃ ⁻ -N	AP	AK
0–10	0.23	0.74	3.64	4.05	63.45	5.39	285.47
10–20	0.39	0.74	3.94	2.03	35.53	3.98	318.18
20–30	0.24	0.73	3.81	3.38	16.31	2.16	270.71
30–40	0.36	0.57	3.71	3.00	5.22	1.41	277.13
40–60	0.37	0.64	2.32	2.86	2.08	2.49	260.45
60–80	0.31	0.65	2.51	4.20	1.28	1.25	192.45
80–100	0.28	0.58	1.18	3.95	0.80	1.49	130.87
100–120	0.18	0.53	1.10	2.68	0.88	1.21	100.24

TN total nitrogen, TP total phosphorous, OC organic carbon, NH₄⁺-N ammonium nitrogen, NO₃⁻-N nitrate nitrogen, AP available phosphorus, AK available potassium

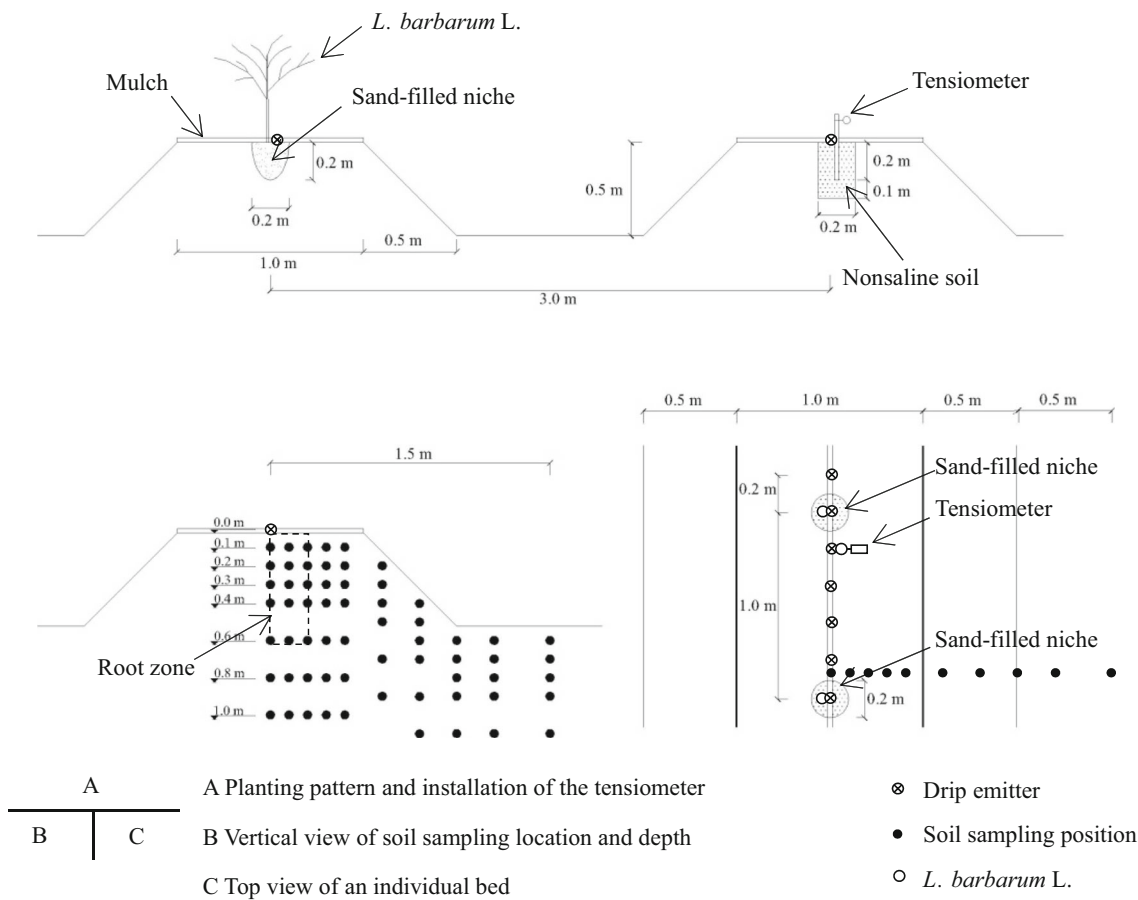


Fig. 1 Planting pattern and soil sampling position. **a** Planting pattern and installation of the tensiometer. **b** Vertical view of soil sampling location and depth. **c** Top view of an individual bed

Saturated soil pastes were prepared for the chemical analyses. Soil pH_s was measured with a pH meter (PHS-3 C, Rex, Shanghai, China). Then, clear extracts of the saturated soil pastes were obtained by centrifugation (4000 rpm, 30 min) and analyzed for EC_e and soluble cations, including Ca²⁺, Mg²⁺, and Na⁺. EC_e was measured with a conductivity meter (DDS-11A, Rex). Ca²⁺ and Mg²⁺ were measured by an EDTA titration method and Na⁺ by flame photometry as described by Bao (2000). SAR was calculated as follows:

$$SAR = \frac{[Na^+]}{([Ca^{2+}] + [Mg^{2+}])^{0.5}}$$

where the concentration of each cation is in millimoles per liter. Then, the EC_e/SAR value was calculated.

Soil total nitrogen (TN) content was determined by the Kjeldahl method and total phosphorous (TP) by a plasma spectrometer after the soil samples had been digested with H₂SO₄. Soil organic carbon (OC) concentration was measured by the dichromate oxidation method. Soil ammonium nitrogen (NH₄⁺-N) and nitrate nitrogen (NO₃⁻-N) were measured by spectrophotometry after the soil samples were extracted with 1 mol L⁻¹ KCl. Available phosphorous (AP) was measured by the molybdenum–antimony anti-spectrophotometric method and available potassium (AK) by flame photometry (Bao 2000).

Table 3 Salinity and ionic composition in irrigation water

EC (dS m ⁻¹)	pH	SAR (mmol L ⁻¹) ^{0.5}	Ionic concentration (mmol L ⁻¹)							
			CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	Mg ²⁺	Ca ²⁺	K ⁺	Na ⁺
2.14	8.87	6.02	0.38	7.75	10.34	1.21	3.23	0.66	0.34	11.88

EC electrical conductivity, SAR sodium adsorption ratio

Table 4 Irrigation, rainfall, evaporation, and fertilization during the growing seasons of *Lycium barbarum* L.

Year	Treatments	Irrigation amount (mm)	Irrigation interval (days) ^a	Rainfall (mm)	Evaporation (mm) ^b	Fertilization rate (kg ha ⁻¹)		
						N	P ₂ O ₅	K ₂ O
2009	S1 (-5 kPa)	160	6.3	153.5	1309.2	160	100	75
	S2 (-10 kPa)	140	10.5					
	S3 (-15 kPa)	130	15.8					
	S4 (-20 kPa)	130	15.8					
	S5 (-25 kPa)	125	21.0					
2010	S1 (-5 kPa)	220	4.2	150.3	1475.1	300	150	100
	S2 (-10 kPa)	180	5.2					
	S3 (-15 kPa)	150	6.4					
	S4 (-20 kPa)	125	7.7					
	S5 (-25 kPa)	105	9.4					
2011	S1 (-5 kPa)	405	2.3	120.8	1490.8	500	240	50
	S2 (-10 kPa)	315	3.0					
	S3 (-15 kPa)	280	3.3					
	S4 (-20 kPa)	220	4.3					
	S5 (-25 kPa)	190	5.0					

^a Irrigation interval refers to the average number of days between irrigation events during treatment period

^b Evaporation refers to cumulative evaporation of a standard evaporimeter with 20 cm diameter

2.4 Data analysis

According to the in situ observation to the root distribution of *L. barbarum* L. with different years (the data is not published), the root zone was defined as being 20 cm horizontal distance from the drip emitter and 60 cm in depth. The average values of the soil properties in the root zone were calculated as the spatial weighted mean of all samples within this zone, take EC_e, for example:

$$EC_e(i) = \frac{\sum_{k=10,20,30,40,50} \sum_{j=0,10,20} EC_e(i,j,k) \times S(j,k)}{\sum_{k=10,20,30,40,60} \sum_{j=0,10,20} S(j,k)} \quad (1)$$

where EC_e(i) is the spatial weighted mean of EC_e in root zone from transect i, and EC_e(i, j, k) is the EC_e of the soil sample from transect i, in which j is the horizontal distance from drip emitter and k is the sampling depth to soil surface. S(j, k) is the representative area of the soil sample. The other soil properties in root zone were measured by the same calculation above.

When significant treatment effects were detected, multiple comparisons among the treatments were carried out using Duncan’s new multiple range test at the 0.05 probability level. The general linear model method for ANOVA (without repetition) was used to evaluate the main effects of factors on soil water, salt, and nutrient properties in the root zone and on plant growth and yield. Two factors, determination time (n = 3, i.e., 2009, 2010, 2011) and SMP (n = 5, i.e., -5, -10, -15, -20, and -25 kPa), were included. SPSS 11.5 statistical

software (SPSS Inc., Chicago, IL, USA) was used to analyze the data, and the figures were created using Surfer 8.0 (Golden Software Inc., CO, USA) and SigmaPlot 10.0 (Systat Software Inc., CA, USA).

3 Results

3.1 Soil water movement

The spatial distribution of SVMC in the soil transects over the 3 years for the S3 (-15 kPa) treatment is shown in Fig. 2. After planting, a wetted area, where SVMC was above 0.34 cm³ cm⁻³, occurred under the drip lines. The wetted front moved horizontally and vertically in the soil transects as the number of years after planting increased, which indicated that soil infiltration capacity was improving. When mulching was not provided, the SVMC was always low in the surface soil layers on the ridge tops and in the furrows due to the high evaporation rate.

Soil water movement and redistribution within the transects under the other treatments showed similar tendencies to S3 (Fig. 2). The differences among treatments occurred mainly in the root zone beneath the drip line. Figure 3 shows the changes to SVMC in the root zones of the different SMP threshold treatments over the 3 years. The SVMC in 2009 was lower than in 2010 and 2011, but the latter two were not significantly different. In 2010 and 2011, the SVMCs in the root zones under S1, S2, and S3 were around 0.40 cm³ cm⁻³

higher than S4 and S5. This meant that the soils were still not saturated at the higher SMP thresholds (the average saturated SVMC of the native soil at 0–60 cm depth was $0.45 \text{ cm}^3 \text{ cm}^{-3}$). The SVMC in root zones decreased gradually as the SMP thresholds declined from -5 to -25 kPa. Furthermore, a significant linear relationship appeared for the -5 to -25 kPa threshold treatments ($P < 0.05$), and this occurred in all 3 years (Fig. 3).

3.2 Soil salt leaching

The soil salt migration through the soil profile for S3 over the 3 years is shown in Fig. 4. The soil water movement caused a desalted region with an $\text{EC}_e < 4 \text{ dS m}^{-1}$ to form under the drip line. The soil salt was washed out of the root zone, resulting in higher salt accumulation on the dry surface layers of the ridge slopes and furrows.

The effects of the different SMP thresholds on soil salt leaching mainly influenced the root zone. The soil salinity in the root zone has osmotic effects on plants and these often cause physiological drought if they exceed critical limits, which vary for different crops. Figure 5 shows the average soil EC_e , pH_s , and SAR in the root zones under the different SMP treatments for 2009–2011. The corresponding initial value in uncultivated soil is also given. Three years after planting, the average soil EC_e was smallest in the root zone under S1 (3.26 dS m^{-1}). This value was lower than the definition value for saline soil ($\text{EC}_e > 4 \text{ dS m}^{-1}$) (US Salinity Laboratory Staff 1954; Amini et al. 2016). S5 produced the highest root zone soil EC_e (9.19 dS m^{-1}), which was significantly lower than the initial value ($P < 0.05$). Three years after planting, the soil salt leaching rates in the S1–S5 root zones were 68.16, 39.45, 26.56, 25.14, and 10.40%, respectively, compared to the initial value. The results suggest that soil water movement had increased soil salt leaching and effectively removed salt from the root zone and that the higher SMP thresholds, such as -5 kPa, improved salt leaching.

The SAR is used to assess the potential for excessive Na^+ to cause soil structure deterioration (Qadir et al. 2001). Soil salt leaching caused the average soil SAR in the root zone to decrease significantly under all treatments (Fig. 5). In the first year, the soil SAR decline in the root zone was about 50%, from $39 \text{ (mmol L}^{-1})^{0.5}$ to $<20 \text{ (mmol L}^{-1})^{0.5}$ under all treatments, but the magnitude of the decrease in SAR was lower in the two subsequent years, which was similar to the results reported by Zia et al. (2006). Three years after planting, the lowest SAR was noted when the SMP threshold was higher than -5 kPa (S1), i.e., $9.59 \text{ (mmol L}^{-1})^{0.5}$, which was lower than 13, a critical limit for sodic soil (US Salinity Laboratory Staff 1954; Amini et al. 2016). The reduction was up to 75.32% compared to the initial value. The highest SAR was seen in S5, i.e., $18.44 \text{ (mmol L}^{-1})^{0.5}$, which represented a 52.56% reduction compared to the initial value.

The adverse effect of excessive Na^+ on soil hydraulic conductivity is magnified by the high soil pH in semiarid and arid regions, because changes in pH affect the edge charge on clays and hence the dispersion (Suarez et al. 1984). Plants that had been growing for just 1 year did not significantly decrease soil pH_s in the root zone compared to the initial pH_s , and there were no significant differences between treatments. This was probably due to the small amount of irrigation applied during the juvenile stage of the plant. In the two subsequent years, soil pH_s in the root zone decreased considerably. After 3 years, S1 produced the largest decline in soil pH_s , i.e., 15.3% of the initial value before planting. The soil pH_s in the S1, S2, and S3 root zones were 7.9, 8.4, and 8.5, respectively, which were lower than 8.5, a critical limit for sodic soil (US Salinity Laboratory Staff 1954; Amini et al. 2016).

3.3 Soil EC_e/SAR ratio

In this study, the EC_e/SAR ratio in the initial soil profile was generally between 0.2 and 0.4 (Table 1). After planting, the soil EC_e/SAR ratio increased, especially in the root zone beneath the drip line (Fig. 6). S1, which was subject to the highest SMP threshold, had the largest root zone EC_e/SAR ratio, at around 0.7, and S5, which had the lowest SMP threshold, had the smallest region of increased soil EC_e/SAR beneath the drip line (Fig. 6).

3.4 Soil nutrient status

In this study, a low TN content of only $0.23\text{--}0.39 \text{ g kg}^{-1}$ was recorded in the uncultivated soil (Table 2). Figure 7 shows the spatial distribution of TN in the soil transects over the 3 years for S3. After 1, 2, and 3 years' plant growth, the average TN contents in the root zones were 0.36 , 0.47 , and 0.50 g kg^{-1} , respectively, and the rates of increase were 18.0, 54.1, and 63.9%, respectively, compared to the initial value in uncultivated soils. TN also rose in the surface layers of the ridge slopes and furrows after 3 years (Fig. 7).

In the uncultivated soils, the TP content ranged between 0.57 and 0.74 g kg^{-1} . After 3 years of plant growth, TP only increased in the small region beneath the drip line, and there were few changes in other soil transect areas (Fig. 7). Fertilization is probably the main causes of increased TP. In particular, phosphorus shows little migration in soil water compared to nitrogen. Therefore, the applied phosphorus did not move very far and accumulated in a small region near the drip emitter.

Generally, salt-affected soils in arid and semiarid areas have low OC contents (Wang et al. 1993), and our soils were no exception. The OC content in the uncultivated soil was only $1.10\text{--}3.94 \text{ g kg}^{-1}$ and decreased gradually with increasing soil depth. The OC spatial distribution in the soil transects after planting is shown in Fig. 7. The weighted mean for OC

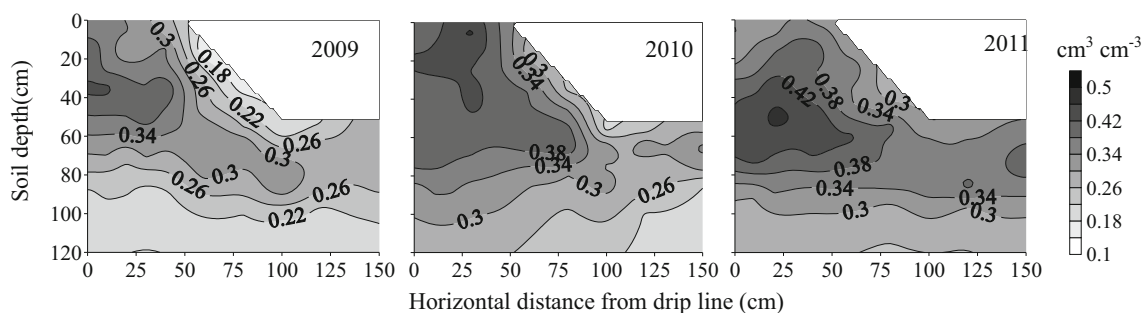


Fig. 2 The spatial distribution of soil volumetric moisture under S3 (−15 kPa) treatment at the end of growing seasons of *Lycium barbarum* L. in different years

content in the root zones at 1 and 2 years after planting were 3.58 and 3.15 g kg^{−1}, respectively, which showed a declined of 5.1 and 16.5%, respectively, compared to the uncultivated soil. At 3 years after planting, the average OC content in the root zone was 4.39 g kg^{−1}, which showed an increase of 16.3% compared to the uncultivated soil.

The soil available nutrient contents in the root zone can reflect soil productivity (plant growth) more directly than whole soil transects. Figure 8 shows the relationship between soil available nutrient status in the root zone and the different SMP thresholds over the 3 years.

In an alkaline environment, NH₄⁺ is often volatilized into NH₃ (Bao 2000), which explains the low NH₄⁺-N content in this high-pH soil. Although significant increases in NH₄⁺-N content were seen after 2 and 3 years, the values were still lower than 20 mg kg^{−1} and decreased significantly as the SMP thresholds declined from −5 to −25 kPa (Fig. 8).

Considerable increases were seen in soil NO₃[−]-N contents in the root zone after planting, and most treatments led a relatively higher NO₃[−]-N content in the root zone, i.e., >100 mg kg^{−1}. The soil NO₃[−]-N contents in the root zones at 2 and 3 years after planting increased significantly as the SMP thresholds declined, which was in contrast to NH₄⁺-N

levels. This was probably due to the mobility of NO₃[−]-N in the applied water. Under the higher SMP treatments, e.g., S1, more irrigation events were applied during the growth period, and less fertilizer was applied per irrigation event. Therefore, the highly mobile soil NO₃[−]-N could be transported out of the root zone.

In the uncultivated soil, the AP content was only between 1.21 and 5.39 mg kg^{−1} and decreased with increasing soil depth (Table 1). However, at 2 and 3 years after planting, soil AP contents increased sharply in the root zones, especially under the higher SMP treatments. Furthermore, the AP contents decreased logarithmically ($P < 0.05$) as the SMP thresholds declined (Fig. 8).

A relatively high AK content was seen in the uncultivated soil (>200 mg kg^{−1} in the soil at 60 cm depth) (Table 2). Therefore, only a small amount of potassium fertilizer was applied during reclamation. Over the 3-year trial period, the soil AK content in the root zones did not change much and there were no significant differences between treatments (Fig. 8).

3.5 Plant growth and yield

An average survival rate of 83.8% was obtained in the first year, but after three growing seasons, S1 had the lowest survival rate (56.8%) and S3 had the highest (81.1%) (Table 5). There are two possible reasons for this. First, the larger volumes of water applied in S1 produced a deterioration in soil aeration, which reduced crop growth. Second, the weak waterlogging tolerance of the plant might inhibit plant growth after salt injury had been relieved.

A wolfberry dry fruit yield of 45.0–56.8 kg ha^{−1} was obtained in the first year, with no significant differences among treatments (Table 4). The yield increased significantly in the second year, and the S1 and S2 yields were more than 450 kg ha^{−1}, which were higher than the other treatments ($P < 0.05$). In the third year, the plants were gradually entering their fully productive stage. Non-significant ($P < 0.05$) differences were found among the dry fruit yields from S2, S3, and S4, which were around 900 kg ha^{−1}. This value was close to

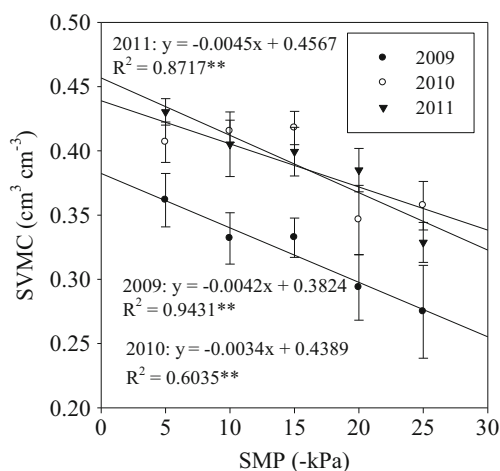


Fig. 3 The changes of soil volumetric moisture content (SVMC) in root zone with soil matric potential (SMP) threshold values

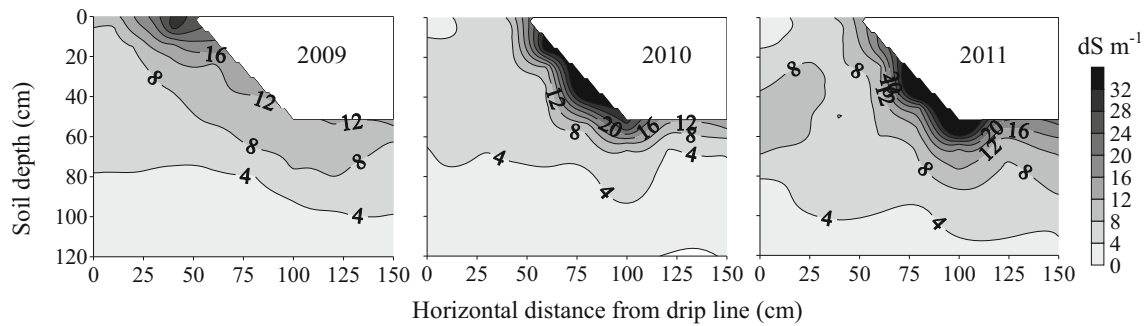


Fig. 4 The spatial distribution of soil EC_e in soil transects under S3 (-15 kPa) treatment at the end of growing seasons of *Lycium barbarum* L. in different years

the levels produced by local farmland and significantly higher than S5 and S1, which produced the lowest yields.

4 Discussion

4.1 Infiltration of saline–sodic/sodic soil

In saline–sodic and sodic soils, sodicity alters soil physical properties directly. It causes a deterioration in soil structure because of increased swelling, dispersion, and slaking upon wetting and increased crusting and hard setting on drying, which produces a concomitant decline in permeability (Oster and Shainberg 2001). The studied area contains a large area of saline–sodic barren land, and the already low rainfall tends to in the low-lying patches and is lost through evaporation. Oster and Jayawardane (1998) suggested that a commonly encountered physical problem with sodic soil is slow water infiltration, which results in low soil water storage, and, for irrigated agriculture, the need is to irrigate more frequently. Drip irrigation is one of the most effective irrigation techniques used to facilitate soil infiltration (Burt and Isbell 2005; Rajak et al. 2006). However, a pre-experiment showed that drip irrigation without sand-filled niches beneath the drip emitters, at a flow rate of <0.76 L h^{-1} , could quickly lead to a thin saturated and impermeable layer beneath the drip emitters, which resulted in surface runoff. This indicated that impermeability was the key factor hindering the amelioration of takyric solonetz. However, drip irrigation alone cannot alleviate this problem.

A previous study showed that the adverse effects of sodicity on soil infiltration and structure are enhanced when the soil is saturated by irrigation water (Oster and Shainberg 2001). Reclamation under an unsaturated soil moisture flow can save water and be more effective in leaching salt than saturated moisture flow (Selassie et al. 1992). In addition, because of the mechanical impact and the stirring action of the applied water, the soil structure in the surface layer is more unstable than the underlying soil. This is also one of the reasons for film mulching when planting. Based on the above, we decided remove the soil from a niche beneath drip emitter and

replace it with sand. The plants were then planted in the sand-filled niches. The specific purposes of the sand-filled niche can be summarized as follows: (1) to expand the water–soil contact area, thereby increasing the area over which infiltration of applied water occurs; this allows the water application rates to be reduced to values that more closely matched the saturated hydraulic conductivity of the native soil; (2) to provide a reservoir to hold the applied water before it infiltrates the native soil; and (3) to alleviate the stirring action of applied water on the surface soil. Our trial results showed that the sand-filled niches under drip emitters facilitated the infiltration

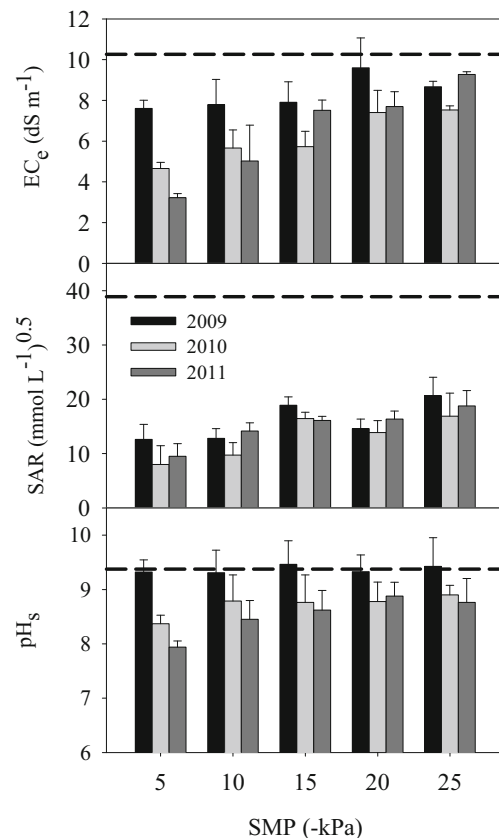


Fig. 5 The soil salt properties in root zone under different soil matric potential (SMP) treatments after 3 planting years. The black dotted line is the initial value before planting

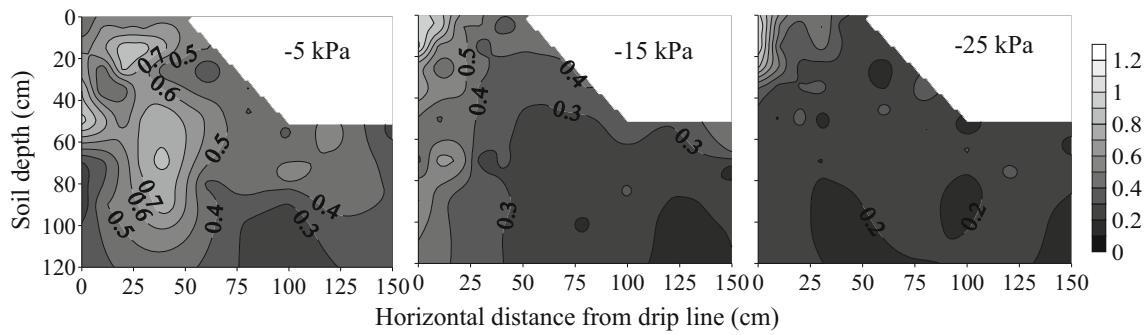


Fig. 6 The spatial distribution of soil EC_e/SAR ratio in soil transects under different soil matric potential treatments after planting for 3 years

of applied water and that the soil water content changed significantly in all the soil layers.

Saline–sodic and sodic soils usually have poor physical and chemical properties, particularly when the electrolyte or dissolved salt concentration of the soil solution (salinity) is unable to compensate for the effects of exchangeable sodium on clay swelling and dispersion. Therefore, the soil EC_e/SAR ratio is an important indicator that reflects changes in soil physical properties during the reclamation process (Rasouli et al. 2013; Nan et al. 2016). Soil hydraulic conductivity

decreases as the ESP increases and the salt concentration of the soil solution decreases (Quirk and Schofield 1955; Quirk 2001). Previous studies have shown that soil dispersion occurs at a very low SAR if the EC_e/SAR ratio is also low (McNeal and Coleman 1966).

In the uncultivated soil, the relatively low EC_e and high SAR resulted in a decreased EC_e/SAR ratio (<0.2). This value would cause a reduction in soil infiltration (Oster and Jayawardane 1998). After planting, the soil EC_e/SAR ratio in the root zone was around 0.7 and hydraulic conductivity

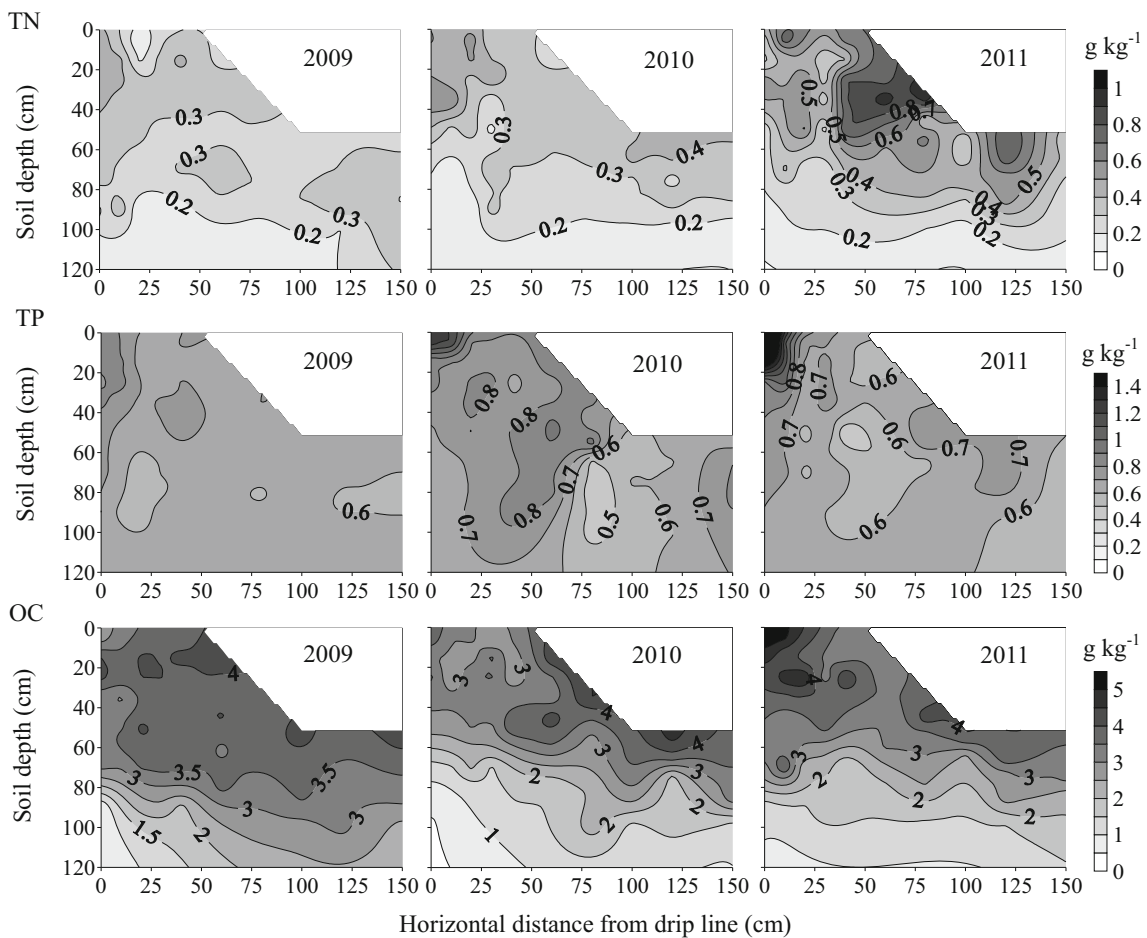
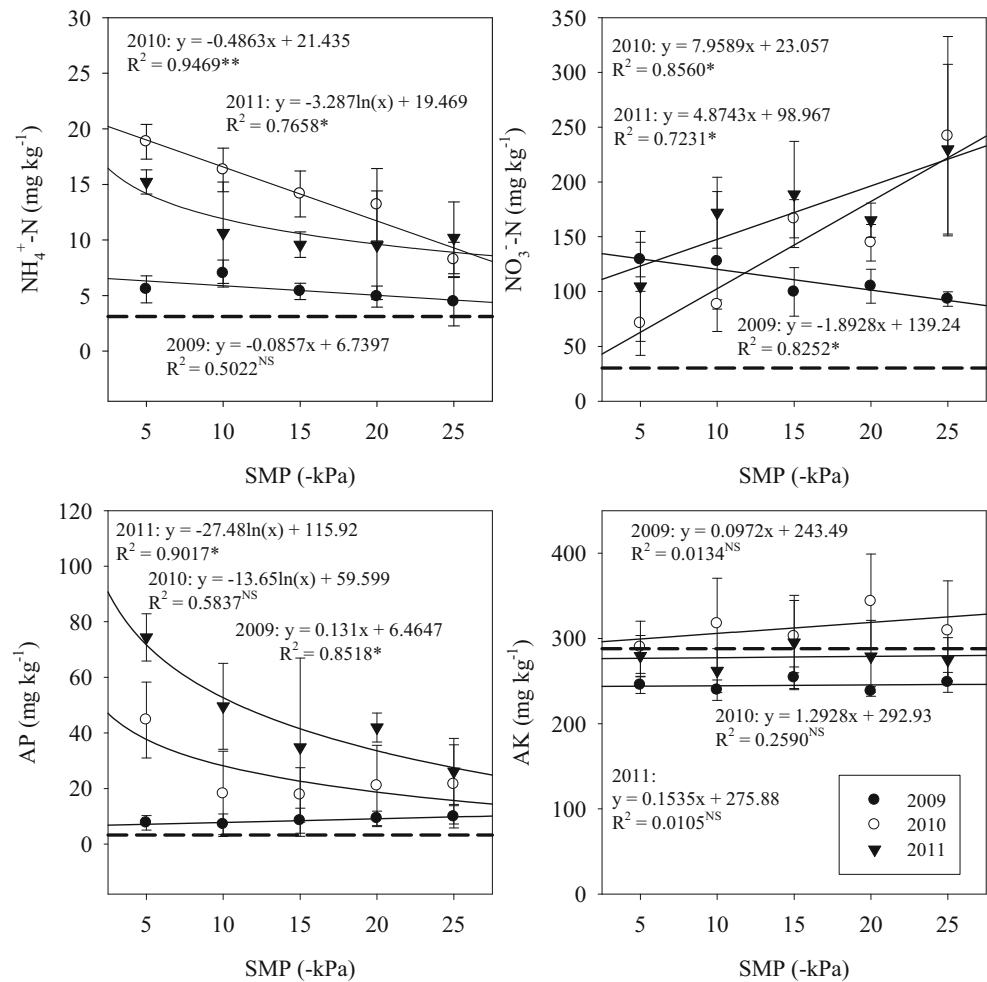


Fig. 7 The spatial distribution of total nitrogen (TN), total phosphorus (TP) and organic carbon (OC) in soil transects under S3 (–15 kPa) treatment at the end of growing seasons of *Lycium barbarum* L. in different years

Fig. 8 The changes of soil ammonium nitrogen (NH_4^+-N), nitrate nitrogen ($NO_3^- -N$), available phosphorus (AP), and available potassium (AK) contents in root zone with the soil matric potential (SMP) threshold values in different years. The black dotted line is the initial value before planting



should not fall below this value (Ayers and Westcot 1985; Oster and Jayawardane 1998). It can be concluded that once the problem with infiltration rates at the soil surface due to a poor combination of EC_e and SAR is solved by drip irrigation and the sand-filled niches beneath drip emitters, the hydraulic conductivity of the soil below the surface is no longer limiting. Additionally, after SAR was reduced, the electrolyte concentration of the irrigation water ($EC = 2.1 \text{ dS m}^{-1}$) was expected to be more or less able to maintain soil hydraulic conductivity in the vicinity of the emitter.

Additionally, calcite dissolution in native soil is enhanced by an increase in partial pressures of carbon dioxide in the soil due to the microbial and root respiration and decomposition of organic matter, and this ultimately facilitates Ca^{2+} replacing exchangeable Na^+ , which leads to the flocculation of dispersed clay. And, furthermore, the plant roots could release exudates causing coagulation of the dispersed clay and improve of soil structure (Chi et al. 2012). So, it was stated that the efficiency of amelioration cannot last for long without plant cultivation (Wang et al. 2012).

Table 5 Survival rates and dry fruit yields of *Lycium barbarum* L. in different years

Treatments	Survival rates (%)			Dry fruit yield (kg ha^{-1})		
	2009	2010	2011	2009	2010	2011
S1 (-5 kPa)	86.4a	81.1a	56.8c	$48.5 \pm 10a$	$465.8 \pm 44.1a$	$698.5 \pm 49.0c$
S2 (-10 kPa)	80.3a	78.8a	75.8ab	$54.2 \pm 4.2a$	$456.3 \pm 29.1a$	$908.8 \pm 24.7a$
S3 (-15 kPa)	83.3a	81.8a	81.1a	$45.0 \pm 4.0a$	$375.7 \pm 14.6b$	$865.7 \pm 63.9ab$
S4 (-20 kPa)	86.4a	84.8a	79.5ab	$56.8 \pm 7.8a$	$337.5 \pm 31.7c$	$863.7 \pm 27.4ab$
S5 (-25 kPa)	82.6a	80.3a	72.7b	$51.4 \pm 16.0a$	$395.1 \pm 34.9b$	$809.5 \pm 62.9b$

Note: Values followed by different letters within the same column differ significantly at $P < 0.05$

4.2 Improvement in soil fertility

Soil structural decline with increasing sodicity reduces nutrient mobility, which leads to nutrient deficiencies (Wong 2010). Therefore, during the reclamation of salt-affected soils, it is also necessary to improve soil fertility and productivity as well as leaching away the excessive soluble salt. The soil available nutrient contents in the root zone are directly related to the growth and yields of plants, and to soil productivity.

After planting, the accumulation of soil nitrogen in the root zone was mainly caused by adding urea with the applied water. The increase in soil inorganic nitrogen in the root zone facilitated nutrient uptake by plant roots. Furthermore, increased soil NO_3^- -N also occurred in the surface layers of ridge slopes and furrows. The following are the two reasons that contributed to these increases: (1) NO_3^- -N is more mobile in water compared to NH_4^+ -N and was leached to a greater distance from the drip emitter, which confirmed the results of previous studies (Li et al. 2003; Yazdanpanah et al. 2013; Wang et al. 2015); and (2) 3 years after planting, the *L. barbarum* L. entered a vigorous growth period and weeds began appearing in the furrow. The increasing plant litter and rhizosphere residue levels increased soil organic nitrogen, which was degraded into inorganic nitrogen by the simultaneous rise in microbial activity. The accumulation of inorganic nitrogen (especially NO_3^- -N) in the surface layer of the ridge slope partly reflected the loss of nitrogen nutrition caused by leaching. Therefore, nitrogen fertilizer should be applied in the latter half of an irrigation event to reduce nitrogen leaching and to improve fertilizer use efficiency (Hanson et al. 2006).

The soil TP content is greatly influenced by the soil parent materials, soil formation, tillage methods, and fertilization (Bao 2000). A soil with a low TP content generally lacks AP. However, in a soil with a high TP content, AP is not necessarily sufficient for crop growth. The AP content of our soil was low (1.21–5.39 mg kg⁻¹) compared to TP (0.53–0.74 g kg⁻¹). Like many soils developed from Loess parent material and distributed widely across the chief agricultural areas of China (Bao 2000), takyric solonetz is calcareous soil and the existing CaCO_3 absorbs considerable amount of phosphorus in the form of calcium phosphate, which is only slightly soluble in water. This restricts phosphorus availability (Qadir et al. 1997).

A number of factors could contribute to the increase in AP after planting. The formation of soluble phosphate, e.g., Na_3PO_4 , after applying phosphoric acid is probably the main reason for the increased AP. Furthermore, the mineralization of organic phosphorous and the dissolution of the slightly soluble phosphorous compounds as the soil pH declines activates some of the previously unavailable phosphorous in the soil. For example, Bao (2000) stated that the phosphorous absorbed by calcium carbonate was released into the soil solution after the dissolution of the original calcium carbonate

because of the declining soil pH. Our results showed that the AP content in the soil was relatively low and it was necessary to apply phosphate fertilizer to meet crop growth needs.

A previous study has suggested that enzyme activities related to the hydrolysis of carbohydrates increased after N application (Geisseler and Horwat 2009) and that organic matter was degraded to satisfy the absorption and utilization of nutrients during plant growth. No organic fertilizer was applied in this study, which probably resulted in the OC content decline in the root zone over the first 2 years. However, after 3 years, the increases in plant litters and rhizosphere residues returned nutrients to the soil, which supplemented the degradation of the original organic matter and, subsequently, increased the soil OC content.

The salt-affected soils in the arid area of northwest China are generally rich in potassium and the soil investigated in this study was no exception (Wang et al. 1993). This is because the main soil parent material is mica (illite), which is high in AK. Therefore, during the reclamation, only a small quantity of potassium fertilizer was applied. After 3 years, the AK content in the root zone decreased slightly as the potassium demand for plant growth increased. When the plants enter the vigorous growth stage and the demand of potassium increases, it becomes necessary to moderately supplement potassium with fertilizer.

4.3 Plant growth responses to SMP

China is the main supplier of wolfberry products in the world. The majority of commercially produced wolfberries come from Ningxia, northwest China. *L. barbarum* L. is also planted in arid areas to reclaim irrigable soils from salinization and desertification.

In the initial stage of reclamation (first 2 years), which was also the juvenile stage of *L. barbarum* L. growth, a higher SMP improved salt leaching and the formation of a low-salinity soil environment. This meant that yields were greater under the higher SMP (between –5 and –10 kPa) treatments than under the lower SMP treatments. In the third year, as the plants began to mature and flourish, the soil properties had considerably improved, and the yields under the –10 to –20 kPa SMP treatments were higher. The decrease in suitable SMP for crop growth during reclamation in this investigation confirmed the results of previous studies in other salt-affected soils (Jiao et al. 2008; Wang et al. 2011; Wan et al. 2012). The wolfberry yield response to SMP in the third year was consistent with that of the same crop in non-saline soils on the Ningxia Plain, where an SMP of –20 kPa is recommended as a trigger for drip irrigation (Jia 2012). Our results show that during the reclamation of highly salt-affected soils, the soil environment gradually improves as the number of years after planting increased and that the most suitable SMP for crop growth decreased. These changes in suitable SMP are

important characteristics that influence salt-affected soil reclamation.

5 Conclusions

In the first 2 years of reclamation, the higher SMP was recommended for its higher salt leaching rate in root zone. And the soil physical properties were also improved after 3 years, indicated by the increased soil EC_s/SAR ratios. Soil nutrient status was considerably improved, and N fertilizer, which was often leached away, should be applied in the latter half of an irrigation event. Additionally, it was necessary to apply adequate P fertilizer to meet crop growth needs for its low AP content, while moderate supplement of K fertilizer was proposed for its richness in K. After 3 years, S2, S3, and S4 produced the significantly higher dry fruit yields (~900 kg ha⁻¹), which were close to those produced by local farmland.

In a word, an improved drip irrigation made the reclamation of an impermeable saline–sodic soil possible. The key operations included drip irrigation, sand-filled niches beneath drip emitters, ridge tillage, film mulching, and the use of thresholds to control SMP.

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References

- Akhter J, Murray R, Mahmood K, Malik KA, Ahmed S (2004) Improvement of degraded physical properties of a saline-sodic soil by reclamation with kallargrass (*Leptochloa fusca*). *Plant Soil* 258: 207–216
- Amini S, Ghadiri H, Chen C, Marschner P (2016) Salt-affected soils, reclamation, carbon dynamics, and biochar: a review. *J Soils Sediments* 16:939–953
- Ayars JE, Phene CJ, Hutmacher RB, Davis KR, Schoneman RA, Vail SS, Mead RM (1999) Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. *Agr Water Manage* 42:1–27
- Ayers RS, Westcot DW (1985) Water quality for agriculture. FAO Irrig. and Dr. Paper 29 Rev.1
- Bao SD (2000) Soil analysis in agricultural chemistry. China Agricultural Press, Beijing
- Basile A, Buttafuoco G, Mele G, Tedeschi A (2012) Complementary techniques to assess physical properties of a fine soil irrigated with saline water. *Environ Earth Sci* 66:1797–1807
- Batchelor CH, Lovell CJ, Murata M (1996) Simple microirrigation techniques for improving irrigation efficiency on vegetable gardens. *Agr Water Manage* 32:37–48
- Burt CM, Isbell B (2005) Leaching of accumulated soil salinity under drip irrigation. *Trans ASAE* 48:2115–2121
- Chi CM, Zhao CW, Sun XJ, Wang ZC (2012) Reclamation of saline-sodic soil properties and improvement of rice (*Oriza sativa* L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China. *Geoderma* 187–188:12–30
- Comprehensive Exploration Team in Department of Agriculture, Ningxia (1963) Soils in Yinchuan Plain. Ningxia People’s Press, Yinchuan
- Geisseler D, Horwath WR (2009) Relationship between carbon and nitrogen availability and extracellular enzyme activities in soil. *Pedobiologia* 53(1):87–98
- Hanson BR, Šimůnek J, Hopmans JW (2006) Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modeling. *Agr Water Manage* 86(1–2):102–113
- Hanson BR, May DE, Šimůnek J, Hopmans JW, Hutmacher RB (2009) Drip irrigation provides the salinity control needed for profitable irrigation of tomatoes in the San Joaquin Valley. *Calif Agric* 63: 131–136
- Hou Z, Chen W, Li X, Xiu L, Wu L (2009) Effects of salinity and fertigation practice on cotton yield and 15N recovery. *Agr Water Manage* 96:1483–1489
- IUSS Working Group WRB (2007) World reference base for soil resources, first update 2007 [R]. World Soil Resources Reports No. 103. FAO, Rome, 2007
- Jia JS (2012) Study on water and salt regulation and coupling effects of water-fertilizer under drip irrigation in arid area—a case of wolfberry. Postdoctoral Report from Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing
- Jiao Y, Kang Y, Wan S, Sun Z, Liu W, Dong F (2008) Effect of soil matrix potential on the distribution of soil salt under drip irrigation on saline and alkaline land in arid regions. *Transactions of the CSAE* 24(6): 53–58
- Li FH (2006) Soil physical chemistry. Chemical Industry Press, Beijing
- Li J, Zhang J, Ren L (2003) Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. *Irrig Sci* 22: 19–30
- Li X, Kang Y, Wan S, Chen X, Chu L (2015) Reclamation of very heavy coastal saline soil using drip-irrigation with saline water on salt-sensitive plants. *Soil Till Res* 146:159–173
- Li X, Kang Y, Wan S, Chen X, Liu S, Xu J (2016) Response of a salt-sensitive plant to processes of soil reclamation in two saline-sodic, coastal soils using drip irrigation with saline water. *Agr Water Manage* 164:223–234
- McNeal BL, Coleman NT (1966) Effect of solution composition on soil hydraulic conductivity. *Soil Sci Soc Am J* 30:308–312
- Nan J, Chen X, Wang X, Lashari MS, Wang Y, Guo Z, Du Z (2016) Effects of applying flue gas desulfurization gypsum and humic acid on soil physicochemical properties and rapeseed yield of a saline-sodic cropland in the eastern coastal area of China. *J Soils Sediments* 16:38–50
- Oster JD, Jayawardane NS (1998) Agricultural management of sodic soils. In: Summer ME, Naidu R (eds) Sodic soils: distribution, processes, management and environmental consequences. Oxford University Press, New York, pp. 125–147
- Oster JD, Shainberg I (2001) Soil responds to sodicity and salinity: challenges and opportunities. *Aust J Soil Res* 39:1219–1224
- Qadir M, Qureshi RH, Ahmad N (1997) Nutrient availability in a calcareous saline-sodic soil during vegetative bioremediation. *Arid Soil Res Rehab* 11:343–352
- Qadir M, Ghafoor A, Murtaza G (2000) Amelioration strategies for saline soils: a review. *Land Degrad Dev* 11:501–521
- Qadir M, Schubert S, Ghafoor A, Murtaza G (2001) Amelioration strategies for sodic soils: a review. *Land Degrad Dev* 12:357–386
- Quirk JP (2001) The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Aust J Soil Res* 39: 1185–1217
- Quirk JP, Schofield RK (1955) The effect of electrolyte concentration on soil permeability. *J Soil Sci* 6:163–178

- Rajak D, Manjunatha MV, Rajkumar GR, Hebbara M, Minhas PS (2006) Comparative effects of drip and furrow irrigation on the yield and water productivity of cotton (*Gossypium hirsutum* L) in a saline and waterlogged vertisol. *Agr Water Manage* 83:30–36
- Rasouli F, Pouya AK, Karimian N (2013) Wheat yield and physico-chemical properties of a sodic soil from semi-arid area of Iran as affected by applied gypsum. *Geoderma* 193:246–255
- Selassie TG, Jurinak JJ, Dudley LM (1992) Saline and sodic-saline soil reclamation-1st order kinetic model. *Soil Sci* 154:1–7
- Suarez DL, Rhoades JD, Savado R, Grieve CM (1984) Effect of pH on saturated hydraulic conductivity and soil dispersion. *Soil Sci Soc Am J* 48:50–55
- Sun J, Kang Y, Wan S (2013) Effects of an imbedded gravel-sand layer on reclamation of coastal saline soils under drip irrigation and on plant growth. *Agr Water Manage* 123:12–19
- Tan J, Kang Y (2009) Changes in soil properties under the influences of cropping and drip irrigation during the reclamation of severe salt-affected soils. *Agr Sci China* 8(10):1228–1237
- Tedeschi A, Dell'Aquila R (2005) Effects of irrigation with saline waters, at different concentration, on soil physical and chemical characteristics. *Agr Water Manage* 77:308–322
- US Salinity Laboratory Staff (1954) Diagnosis and improvement of saline and alkali soils. *Agriculture Handbook No. 60*, USDA-ARS, Washington, DC
- Wan S, Jiao Y, Kang Y, Hu W, Jiang S, Tan J, Liu W (2012) Drip irrigation of waxy corn (*Zea mays* L. var. *ceratina* Kulesh) for production in highly saline conditions. *Agr Water Manage* 104:210–220
- Wang JZ (1990) Soils in Ningxia. Ningxia People's Press, Yinchuan
- Wang ZQ, Zhu SQ, Yu R, et al. (1993) Salt-affected soils of China. Science Press, Beijing
- Wang B, Xiao GJ, Mao GL, Yue ZH, Xu X (2010) Effects of coal-fired flue gas desulfurated waste residue application on saline-alkali soil amelioration and oil-sunflower growth. *Chin J Plant Eco* 34(10):1227–1235
- Wang R, Kang Y, Wan S, Hu W, Liu S, Liu S (2011) Salt distribution and the growth of cotton under different drip irrigation regimes in a saline area. *Agr Water Manage* 100:58–69
- Wang R, Kang Y, Wan S, Hu W, Liu S, Jiang S, Liu S (2012) Influence of different amounts of irrigation water on salt leaching and cotton growth under drip irrigation in an arid and saline area. *Agr Water Manage* 110:109–117
- Wang R, Kang Y, Wan S (2015) Effects of different drip irrigation regimes on saline-sodic soil nutrients and cotton yield in an arid region of Northwest China. *Agr Water Manage* 153:1–8
- Wong VNL (2010) Soil carbon dynamics in saline and sodic soils: a review. *Soil Use Manage* 26:2–11
- Yazdanpanah N, Pazira E, Neshat A, Mahmoodbadi M, Sinobas LR (2013) Reclamation of calcareous saline sodic soil with different amendments (II): impact on nitrogen, phosphorus and potassium redistribution and on microbial respiration. *Agr Water Manage* 120:39–45
- Yin Y (1985) Soil formation, characteristics and amelioration of takyric solonetz. *Chin J Soil Sc* 16(5):206–208
- Zhang T, Kang Y, Wan S (2013) Shallow sand-filled niches beneath drip emitters made reclamation of an impermeable saline-sodic soil possible while cropping with *Lycium barbarum* L. *Agr Water Manage* 119:54–64
- Zia MH, Ghafoor A, Murtaza G, Saifullah BSMA (2006) Growth response of rice and wheat crops during reclamation of saline-sodic soils. *Pak J Botany* 38(2):249–266