TRANSACTIONS OF THE CHINESE SOCIETY FOR AGRICULTURAL MACHINERY
Vol. 47, No. 10, 2016

doi:10.6041/j.issn.1000-1298.2016.10.019

Amelioration of High Saline-sodic Wasteland of Takyric Solonetz by Cropping *Lycium barbarum* L. with Drip Irrigation and Shallow Sand-filled Niches

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Abstract: Takyric solonetz is spread mainly in arid area, Northwest China. Its poor soil structure and extremely low hydraulic conductivities K_s ($K_s < 0.1$ mm/d) are the key factors restricting its amelioration. The EC_e (electrical conductivity of saturated paste extract), SAR_e (sodium adsorption ratio of saturated paste extract), and $\mathrm{pH_s}$ (pH of saturated paste) of the native soil studied at depth of 0 ~ 30 cm were 12.30 dS/m, 44.12 $(\mathrm{mmol/L})^{0.5}$ and 9.33, respectively. After deep tillage, beds (1.0 m width, 0.5 m height) were formed. The drip lines were placed on beds covered with plastic. *Lycium barbarum* L. seedlings were then planted. A three-year field experiment was conducted to determine if reclamation could be achieved while cropping *Lycium barbarum* L. by using drip irrigation where soil beneath the drip emitters near the plants was replaced with sand in niches that were 0.2 m ground diameter and 0.2 m depth. The purpose of sand-filled niche was to increase the area over which infiltration of water occured thereby reducing the application rates to values that more closely matched the saturated hydraulic conductivity of the native soil, provide a reservoir for holding the applied water before it infiltrated and avoid the adversely mechanical impact and the stirring action of applied water on soil surface. Five treatments based on soil matric potential (SMP) thresholds used to trigger drip irrigation were designed to find the optimal drip irrigation schedule, i.e., −5 kPa (S1), −10 kPa (S2), −15 kPa (S3), −20 kPa (S4) and −25 kPa (S5). The results showed that significant improvement was achieved in soil infiltration capability, which was demonstrated by the increasingly enlarged wetted area beneath the drip emitter. Consequently, a desalt region ($EC_e < 4$ dS/m) was formed, and high SMP level was favorable for the salt-leaching in soil. The ratio of EC_e/SAR_e was increased significantly after planting, which indicated the changes of soil salt composition characteristics and the amelioration of soil physical properties. After planting with drip irrigation, the contents of soil available nutrients were increased sharply. Nitrate nitrogen showed a high migration with water movement, and had potential to be lost by leaching, so nitrogen fertilizer should be applied in the later period during one irrigation event to reduce the leaching of nitrogen and raise fertilizer use efficiency. While available phosphorus was distributed mainly in depth of 0 ~ 20 cm under drip emitter, due to its low migration with water. After three years experiment, S1 had the lowest survival rate (56.8%), and S3 got the highest (81.1%), S2, S3 and S4 gave higher fruit yields than other treatments significantly ($p < 0.05$), which was around 900 kg/hm^2, and it was close to the level in local farmland. The findings indicated that a sand-filled niche beneath the drip emitter could be adopted for the reclamation of highly saline-sodic wasteland of takyric solonetz. Considering the factors, including soil water-salt properties, soil nutrients distribution and the growth of *Lycium barbarum* L., an SMP of −10 kPa in the first two years and −20 kPa from the third year could be used to trigger drip irrigation.

Key words: takyric solonetz; drip irrigation; water regulation; soil matric potential; salt leaching; *Lycium barbarum* L.

0 Introduction

Salt-affected soils are the important reserving land resources in China. Their amelioration has strategic significances for increasing the arable land area and even the sustainable development of whole national

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Received date: 2016-05-17 Accepted date: 2016-07-27
Supported by National High Technology Research and Development Program of China (863 Program) (Grant No. 2013AA102904), National Natural Science Foundation of China (Grant No. 51509238, 41503078), and CAS "Light of West China" Program (Zhang T.)

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economy[1]. Compared with the saline soil, the saline-sodic and sodic soils are more difficult to be reclaimed due to the adverse physical properties of the deteriorated soil structure and low permeability induced by the occurrence of excess Na^+ [2-3]. Improving soil structure and soil permeability are the primary problems to resolve during the amelioration of impermeable saline-sodic and sodic soils[4].

Takyric solonetz, as a highly saline-sodic soil, is spread mainly in arid area, Northwest China[5]. In Ningxia, takyric solonetz, named also as "Baijiang soil", is mainly distributed in Xidatan, Pingluo county, with area of 2×10^4 hm^2 [5-7]. With special landscape and profile, the soil does not support any vegetation except some blue-green algae, such as microcoleus, growing in patches during the monsoon season. A large area of the soil is highly saline-sodic wasteland with bare surface. The typical takyric solonetz has gray crust with depth of only 1 cm in the surface, which was apt to disperse. Below that, the blocky or prismatic soil structure, which is very stiff, often occurs. The differences between this soil and soda saline-alkali soil are the following: the special soil profile of this soil does not occur in the soda saline-alkali soil, although the soda saline-alkali soil has the same excessive Na^+ and high soil pH value, and the mineralization degree of groundwater in the soda saline-alkali soil is low, while the water table is high[6,8]. In recent decades, many methods have been attempted to reclaim this soil, including deep ploughing, application of organic fertilizer, rice cropping along with frequent irrigation and drainage, replacement of the entire surface soil with good soil, and use of chemical amendments. However, most methods were not effective primarily because of the extremely low saturated hydraulic conductivity (K_s) of soils ($K_s <$ 0.1 mm/d), or were difficult to be popularized due to the long amelioration period and high investment[5,8-9].

Drip irrigation, which is characterized by the point source diffusion properties of high frequency and small flow, has smaller destruction than surface irrigation to soil structure. It can result in low soil salinity and adequate soil water, nutrients and aeration in the root zone by precise application of water and nutrients[10]. Soil matric potential (SMP) is an ideal indicator of soil water content, and can be used to schedule optimal field irrigation patterns[11-12]. In recent years, many water and salt regulation methods of drip irrigation based on SMP combined with mulching and ridge planting have been established in varying salt-affected soils, however, most of them were saline soils with good soil permeability[13-15]. If takyric solonetz could be reclaimed through improving the drip irrigation and planting technology, it will contribute to the environmental protection through increasing vegetation cover, and rural poverty reduction through increasing the local agricultural productivity. Additionally, it will also provide a new reclamation method for the saline-sodic and sodic soils with low permeability in the world.

Hence, the aim of this study was to determine the possibility of reclamation of takyric solonetz by drip irrigation through improving the water regulation method and planting technology, which a sand-filled niche beneath drip emitters was adopted. Soil water and salt movement, nutrients distribution and the growth and yield of *Lycium barbarum* L. were studied under different SMP treatments to optimize drip irrigation scheduling.

1 Study area and methods

1.1 Experimental site

The experimental site is located in Xidatan area (38°47′ ~ 38°57′N, 106°20′ ~ 106°30′E, altitude is 1 095 m), Pingluo county, Ningxia Hui Autonomous Region, Northwest China. This area belongs to the semi-arid and semi-desert salt-affected area in upper and middle reaches of Yellow River [5]. The station has typical arid continental climate, with mean annual temperature of 9.4℃, and mean annual precipitation of 178 mm. The mean annual potential evaporation is more than 2 000 mm.

The water table at experimental site was about 2.5 m. The studied takyric solonetz was homogeneous and barren without any vegetation cover. The soil was highly saline-sodic wasteland abandoned for many years. The soil profile was compacted and soil bulk density below 10 cm was more than 1.5 g/cm^3. The electrical conductivity of saturated paste extract (EC_e), sodium adsorption ratio of saturated paste extract (SAR_e), and pH value of saturated paste

(pH_s) of the native soil studied at depth of 0 ~ 30 cm were 12.30 dS/m, 44.12 $(mmol/L)^{0.5}$ and 9.33, respectively. The other soil physicochemical properties were shown in Tab. 1.

Tab. 1 Main physicochemical properties of uncultivated soil

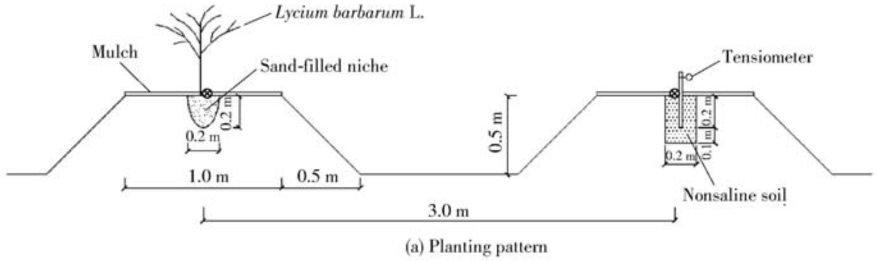
Soil depth/ cm	Bulk density/ ($g \cdot cm^{-3}$)	EC_e/ ($dS \cdot m^{-1}$)	pH_s	SAR_e/ $(mmol \cdot L^{-1})^{0.5}$	EC_e/SAR_e	Available nutrients/($mg \cdot kg^{-1}$)			
						NH_4^+-N	NO_3^--N	AP	AK
0 ~ 10	1.44	18.54	8.90	39.76	0.47	4.05	63.45	5.39	285.47
10 ~ 20	1.53	11.66	9.58	54.01	0.22	2.03	35.53	3.98	318.18
20 ~ 30	1.59	6.69	9.52	38.59	0.17	3.38	16.31	2.16	270.71
30 ~ 40	1.64	4.16	9.51	23.15	0.18	3.00	5.22	1.41	277.13
40 ~ 60	1.60	2.45	9.50	15.43	0.16	2.86	2.08	2.49	260.45
60 ~ 80	1.63	1.89	9.43	7.72	0.24	4.20	1.28	1.25	192.45
80 ~ 100	1.55	1.67	9.24	7.72	0.22	3.95	0.80	1.49	130.87

Note: AP was available phosphorus; AK was available potassium.

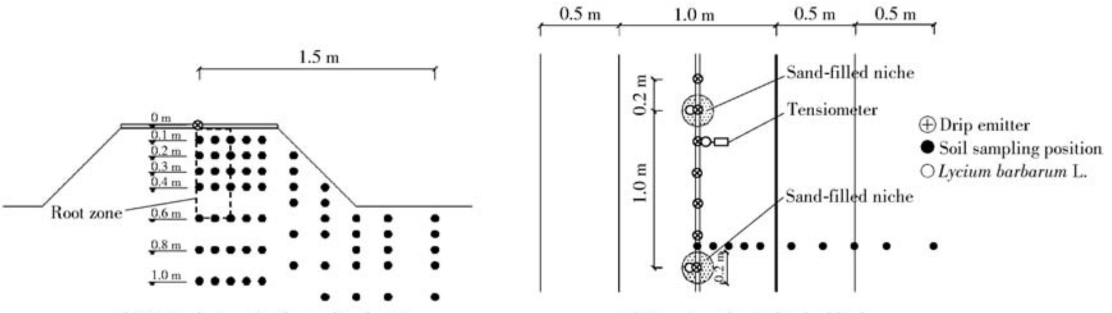
1.2 Experimental design and arrangement

1.2.1 Agronomic practices

Preparation of native soil was made on 23 April 2009, including deep ploughing to a depth of 0.5 m followed by making beds that were 0.5 m in height, 1 m in width, and 3 m between bed centers (Fig. 1a). After raising the beds, semi-ellipsoid pits (with ground surface diameter of 0.2 m, depth of 0.2 m, and volume of about 4.2 L) were dug beneath the emitters, where seedlings of *Lycium barbarum* L. were to be planted (Fig. 1a). The pits were filled with sand. *Lycium barbarum* L. (cultivar: Ningqi No. 1) seedlings were transplanted into the center of beds at intervals of 1 m where the sand-filled niches were located. Drip irrigation lines with emitter spacing of 0.2 m and flow rate of 0.76 L/h at operating pressure of 0.03 MPa were placed onto the center of each raised bed. And the beds were mulched with white polyethylene film (Fig. 1a). Irrigation water, with *EC*, pH value and *SAR* of 2.14 dS/m, 8.87 and 6.02 $(mmol/L)^{0.5}$, respectively, was obtained from a reservoir near the experimental field.



(a) Planting pattern



(b) Vertical view of soil sampling location (c) Top view of an individual bed

Fig. 1 Planting pattern and soil sampling positions

1.2.2 Plot layout and irrigation treatments

The experiment included five water treatments based on SMP, measured with tensiometers located at the depth of 0.2 m beneath the drip emitter (Fig. 1a and Fig. 1c). 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), respectively. Each treatment was done in triplicate (3 × 5 = 15 plots) and laid out permanently following a completely randomized block design, and the size of each plot was 12 m × 12 m which consisted of four raised beds. Each treatment used 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 *Lycium barbarum* L. seedlings on 26 April 2009, 20 mm of water was applied over a period of 3 d to reduce soil salinity near the plant and provide favorable soil moisture for survival of seedlings. After the growth of *Lycium barbarum* L. seedlings was stable, water treatments based on SMP were initiated: 5 mm of water was applied each time when the SMP reached the designed threshold. The irrigation times and amount were recorded. In the following two years, 10 mm of water was applied at the beginning of growing seasons to leach salts brought nearer the surface in winter because of the lack of irrigation and upward water movement as a consequence of the freeze-thaw cycle and direct evaporation of water to air from the soil surface. Thereafter 5 mm of water was applied when SMP reached the threshold for each treatment. The irrigation rates are shown in Tab. 2.

1.2.3 Fertilization and field management

Urea, phosphoric acid and potassium nitrate were added into the fertilizer tank and dissolved in water so that the fertilizer was applied with irrigation water. The same amount of fertilizer was applied for the five treatments (Tab. 2). Like those in local high-yield farmland, field managements included mainly regular pruning, trimming, weeding and application of pesticides to control insects.

Tab. 2 Irrigation, rainfall, evaporation and fertilization during growing seasons of *Lycium barbarum* L.

Year	Treatments	Irrigation depth/mm	Irrigation interval/d	Rainfall/mm	Evaporation/mm	Fertilization rate/(kg·hm^{-2})		
						N	P_2O_5	K_2O
2011(1 a)	S1(−5 kPa)	160	6.3	153.5	1 309.2	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					
2012(2 a)	S1(−5 kPa)	220	4.2	150.3	1 475.1	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					
2013(3 a)	S1(−5 kPa)	405	2.3	120.8	1 490.8	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					

Note: irrigation interval refers to average number of days between irrigation events during treatment period; evaporation refers to cumulative evaporation of a standard evaporimeter with 20 cm diameter.

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. Large amount and long time ponding water was not found during the experimental period. The drainage water was lost mainly by evaporation. The beds, irrigation system, plants, and drainage ditch were not changed during the three year experiment.

1.3 Soil sampling and analysis

Soil samples were obtained from each plot with an auger (diameter 4.0 cm, length 20 cm), at the location shown in Fig. 1b and Fig. 1c, at the end of each growing season (28 October 2009, 18 October 2010 and 16 October 2011). The sampling location was as close as possible to the sand-filled niche to avoid sampling the sand-filled niche (Fig. 1c). The horizontal distances of sampling from drip line were 0 cm, 10 cm, 20 cm, 30 cm, 40 cm, 60 cm, 80 cm, 100 cm, 120 cm and 150 cm. The sampling depths were 0 ~ 10 cm, 10 ~ 20 cm, 20 ~ 30 cm, 30 ~ 40 cm, 40 ~ 60 cm, 60 ~ 80 cm and 80 ~ 100 cm (Fig. 1b). After carefully removing the surface organic materials and fine roots, soil water content was determined gravimetrically in the field moist subsamples. Soil volumetric moisture content (SVMC) was calculated by multiplying gravimetric water content by real-time soil bulk density. The remaining soil subsamples were air-dried, passed through a 1 mm sieve, and then three replicates of soil samples were mixed into one sample to optimize the huge workloads of chemical analysis. The chemical analysis was finished in eight weeks after sampling.

Saturated soil paste was prepared for the chemical analysis. Soil pH values (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 (4 000 r/min, 30 min) and analyzed to obtain EC_e and soluble cations, including Ca^{2+}, Mg^{2+} and Na^+. EC_e was measured with a conductivity meter (DDS - 11A, REX, Shanghai, China). Concentrations of Ca^{2+} and Mg^{2+} were measured by an EDTA titration method and Na^+ was measured by flame photometry. SAR_e was calculated as follow

$$SAR_e = \frac{C_{Na^+}}{(C_{Ca^{2+}} + C_{Mg^{2+}})^{0.5}} \tag{1}$$

where C_{Na^+}, $C_{Ca^{2+}}$, $C_{Mg^{2+}}$ were concentrations of Na^+, Ca^{2+} and Mg^{2+}, mmol/L.

Then, the ratio of EC_e to SAR_e was calculated.

Concentrations of soil ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were measured by spectrophotometry. Available phosphorous (AP) was measured by molybdenum-antimony anti-spectrophotometric method and available potassium (AK) by flame photometry[16].

1.4 Data analysis

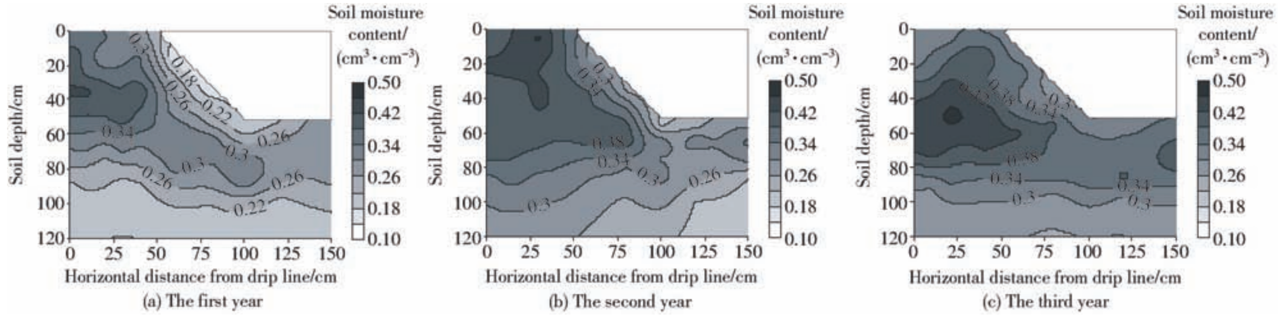
The root zone was defined as a section of 0 ~ 20 cm horizontal distance from the drip emitter and 0 ~ 60 cm at depth, the average values of soil properties in root zone were calculated as the spatial weighted mean of all samples. All the data analyses were conducted by using SPSS 16.0 statistical software (SPSS Inc., Illinois, USA). Figures were created by using Surfer 8.0 (Golden Software Inc., Colorado, USA) and SigmaPlot 10.0 (Systat Software Inc. California, USA).

2 Results and analysis

2.1 Soil water and salt characteristics

2.1.1 Water movement in soil profile

For treatment S3, the spatial distribution of SVMC in the soil transects in different years is shown in Fig. 2. After planting, a wetted area, where SVMC was observed above 0.34 cm^3/cm^3, occurred under the drip lines. The wetting front was moved horizontally and vertically in the soil transects with the increase of planting years, indicating the improvement effects had been exerted on soil infiltration capacity. In the surface soil layer of ridge slop and furrow, SVMC was always low due to the intensive evaporation without mulching.



(a) The first year (b) The second year (c) The third year

Fig. 2 Spatial distributions of soil volumetric moisture content in soil transects at end of growing seasons of *Lycium barbarum* L. in different planting years under S3

The soil water movement and redistribution in transects under other treatments tended tobe the similar tendency as S3 (Fig. 2). The differences among treatments occurred mainly in the root zone beneath drip line. Fig. 3 shows changes of SVMC in root zones with the varying SMP thresholds in different years. The values were the weighted means (in the figure, * and ** indicate the statistical significance at $p < 0.05$ and $p < 0.01$, respectively, NS means no significance. The same below). Among different years, the SVMC of 2009 (the first year) was lower than those of 2010 and 2011, and the latter two gave no significant difference. In 2010 and 2011, the SVMC in root zone under S1, S2 and S3 was around 0.40 cm^3/cm^3, which was

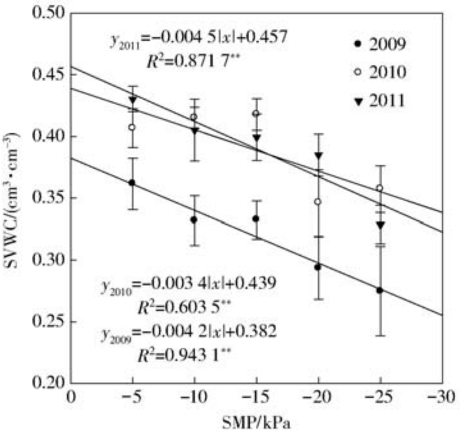
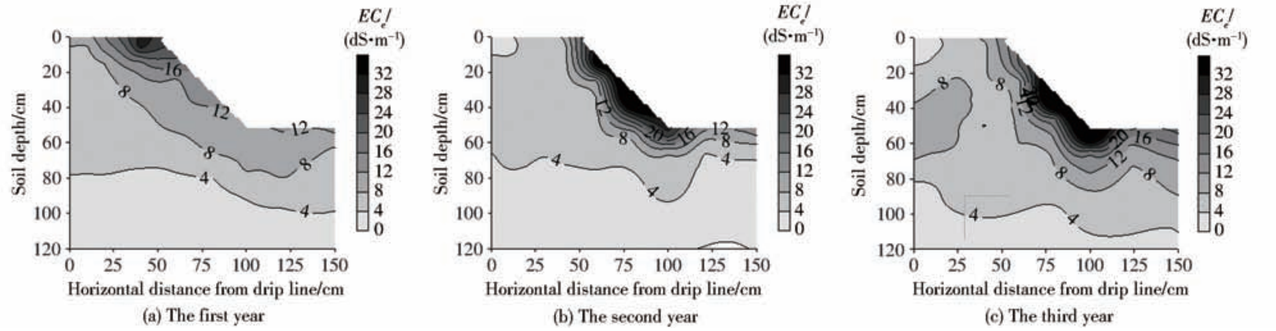


Fig. 3 Changes of average soil volumetric moisture content (SVMC) in root zone with different soil matric potential (SMP) thresholds in different planting years

higher than those under S4 and S5. This value meant that the soils were still not saturated under the higher SMP (the average saturated SVMC of the native soil in 0 ~ 60 cm was 0.45 cm^3/cm^3). As the thresholds of SMP declined from −5 kPa to −25 kPa, SVMC in root zone was decreased gradually. And a significant linear relationship could be found between SVMC and SMP ($p < 0.01$), similarly in the three years.

2.1.2 Soil salt leaching in root zone

Along with soil water movement, soil salt migration in soil profile in different years is shown in Fig. 4 for treatment S3. After drip irrigation, a desalt region with EC_e less than 4 dS/m was formed under the drip line, the soil salt was prone to be distributed in the fringe of wetted regions. With the increase of planting years, the area of desalt region was enlarged gradually. For the whole soil transect, only a little salt was moved down to the lower soil layer, more soil salt was accumulated in the dry surface layer of ridge slop and furrow, which was driven by water leaching of drip irrigation and the intensive evaporation without mulching.



(a) The first year (b) The second year (c) The third year

Fig. 4 Spatial distributions of soil EC_e in soil transects at end of growing seasons of *Lycium barbarum* L. in different planting years under S3

Likely as the soil water, the effectsof treatments on soil salt leaching were mainly instantiated in root zones (Fig. 5, different letters mean the differences is statistically significant at $p < 0.05$. The same below). After planting for three years, the average soil EC_e in root zone under S1, which was controlled with the highest SMP, was the lowest with value of 3.26 dS/m, which was lower than the definition value of saline soil (EC_e more than 4 dS/m) [4]. With the decline of SMP thresholds, the average soil EC_e in root zone was increased gradually, and S5 gave the highest value (9.19 dS/m), which was yet still lower than the initial value significantly ($p < 0.05$). After planting for three years, soil salt leaching rates in root zone for S1 ~ S5 were 68.16%, 39.45%, 26.56%, 25.14% and 10.40%, respectively, compared with the initial

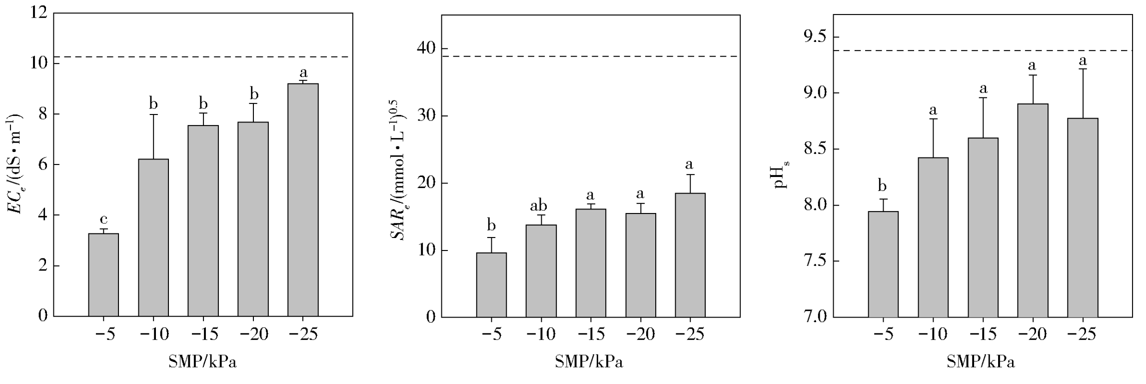


Fig. 5 Soil salt properties in root zone under different soil matric potential (SMP) treatments after three planting years

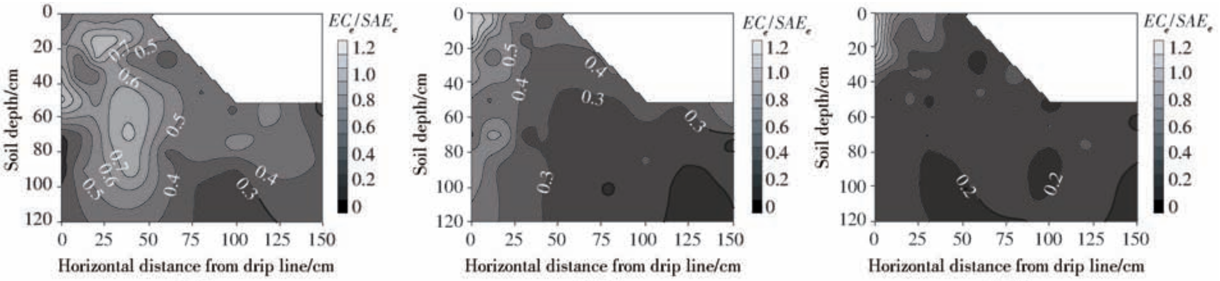
value. It could be included that along with the soil water movement, soil salt was leached effectively outside the root zone, and high SMP threshold was helpful for salt leaching.

With the soil salt leaching, the average soil SAR_e in root zone was decreased significantly under all treatments, and the decreased magnitudes were larger than those of EC_e. This is because SAR_e is a close measure of exchangeable sodium percentage[17]. Na^+ was the main cation in the studied soil[18], and Na^+ has better mobility with water flow than Ca^{2+} and Mg^{2+} because of its smaller adsorption capacity with soil clay[3]. After planting for three years, the decline rate of soil SAR_e in root zone were about 50%, which was reduced to 20 $(mmol/L)^{0.5}$ under all treatments. The lowest SAR_e (9.59 $(mmol/L)^{0.5}$) was noted when SMP threshold was controlled higher than −5 kPa (S1), which was lower than 13 $(mmol/L)^{0.5}$, a critical limit for sodic soil[4]. The decline rate was up to 75.32%. The highest SAR_e (18.44 $(mmol/L)^{0.5}$) was seen in S5, the decline rate was 52.56% compared with the initial value.

After three years, S1 resulted in the largest decline magnitude of soil pH_s, i.e., 15.3% compared with the initial value before planting. The soil pH_s values in root zone of S1, S2 and S3 were 7.9, 8.4 and 8.5, respectively, which were lower than 8.5, a critical limit for sodic soil[7]. Due to the buffer capacity of soil, soil pH value could not change by a large margin in a short period, unlikely as soil salt content.

2.1.3 Soil EC_e/SAR_e ratio

The EC_e/SAR_e ratio in initial soil profile was in the range of 0.2 ~ 0.4 (Tab. 1). Undoubtedly, this level would impose adverse influences on soil physical properties. After planting for three years, the spatial distributions of soil EC_e/SAR_e ratio in soil transects under different treatments were shown in Fig. 6. Soil EC_e/SAR_e ratio was increased after planting, especially in root zone beneath drip line, indicating that soil salt component characteristics also were changed with the soil salt leaching. S1 treated with higher SMP, which had the best salt leaching effect, resulted in the highest EC_e/SAR_e ratio in root zone, which was around 0.7, and the area of increased soil EC_e/SAR_e was decreased gradually with the decline of SMP thresholds (Fig. 6).



(a) S1 (b) S3 (c) S5

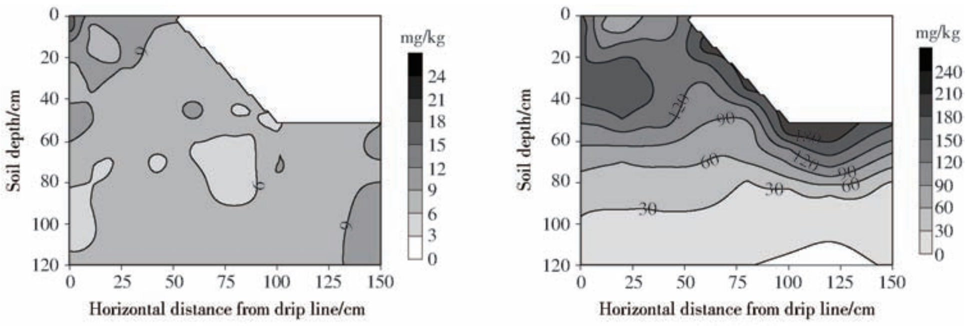
Fig. 6 Spatial distributions of soil EC_e/SAR_e ratio in soil transects after three planting years under different SMP treatments

2.2 Soil nutrients status

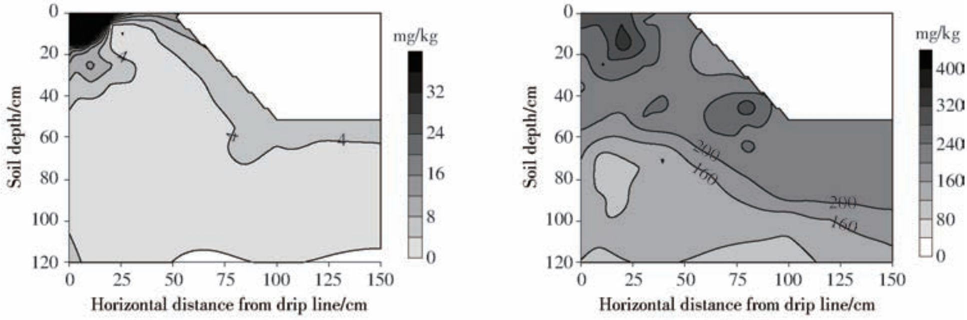
The contents of NH_4^+-N, NO_3^--N and AP were found very low in the uncultivated soil. In alkaline environment, NH_4^+ is prone to be volatilized in the form of NH_3, the NH_4^+-N contents in the studied soil were in the range of 2.86 ~ 4.20 mg/kg (Tab. 1). After planting for three years, the soil NH_4^+-N contents were increased obviously, which was more than 9 mg/kg in root zone (Fig. 7).

In uncultivated soil profile at the depth of 0 ~ 100 cm, the NO_3^--N contents were decreased with the increase of soil depth, it was 63.45 mg/kg in the surface layer and 0.80 mg/kg in the depth of 80 ~ 90 cm (Tab. 1), its average value in 0 ~ 40 cm soil layer was 30.13 mg/kg. Considerable increases were seen in soil NO_3^--N contents after planting, resulting in relatively higher NO_3^--N contents in the whole soil transect, which was more than 60 mg/kg. There were two accumulated regions for soil NO_3^--N: one was the root zone beneath the drip emitter, the other was the surface layer of ridge slope. The NO_3^--N contents were generally more than 100 mg/kg.

In uncultivated soil, the AP content was only in the range of 1.21 ~ 5.39 mg/kg, and decreased with the increase of soil depth (Tab. 1). The average AP content of 0 ~ 40 cm soil was 3.24 mg/kg. After



(a) NH_4^+-N (b) NO_3^--N



(c) AP (d) AK

Fig. 7 Spatial distributions of soil ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (AP) and available potassium (AK) in soil transects after three planting years under S3

planting for three years, soil AP contents increased sharply, which however, accumulated mainly in the small region at the depth of 0 ~ 20 cm beneath the drip emitter (Fig. 7), due to phosphorus showed little migration with water in soil compared to nitrogen[16].

An relatively high AK content was seen in uncultivated soil, in the range of 130.87 ~ 318.18 mg/kg, and decreased with the increasing soil depth. So a small amount of potassium fertilizer was applied during this study. In the three years of trial period, the soil AK content was not changed so much, which was always in a high level as around 200 mg/kg.

After planting, the relationships of soil available nutrients contents in root zone with SMP threshold valuesare shown in Fig. 8. After planting for one year, soil NH_4^+-N contents were increased moderately compared with the initial value, and no significant differences were seen among treatments. After two and three years, the soil NH_4^+-N contents in root zone were increased significantly, and decreased gradually with the decline of SMP threshold (from -5 kPa to -25 kPa), showing linear and logarithmic relationships ($p < 0.05$), respectively.

Soil NO_3^--N contents were increased considerably after drip irrigation. After one year planting, the soil NO_3^--N contents in root zone were decreased with the decline of SMP threshold, and only minor differences were detected among treatments. While contrary to that of one year planting, the soil NO_3^--N contents in root zone planted for two and three years were increased significantly with the decline of SMP threshold ($p < 0.05$). This was probably because that more fertilizers were applied with increase of planting ages, and under the treatments with lower SMP, e. g. S5, and more fertilization amount was applied in one irrigation event, so more N fertilizer accumulated in the root zone beneath drip emitter.

With the increase of planting years, the soil AP contents in root zone were increased gradually. The AP contents were decreased with the decline of SMP threshold logarithmically, and S1 gave the highest AP content. This was due to the low mobility of AP with water flow, resulting in more phosphate ion distributed uniformly in the root zone under higher SMP treatments irrigated more frequently. Because of the small amount of K fertilization during planting, it showed little changes in soil AK contents, and no significant difference was seen among treatments.

Overall, soil available nutrients contents in root zone planted for onlyone year were still low, and little difference existed among treatments, while after planting for two years, soil available nutrients contents were increased significantly, and the differences among treatments were also increased.

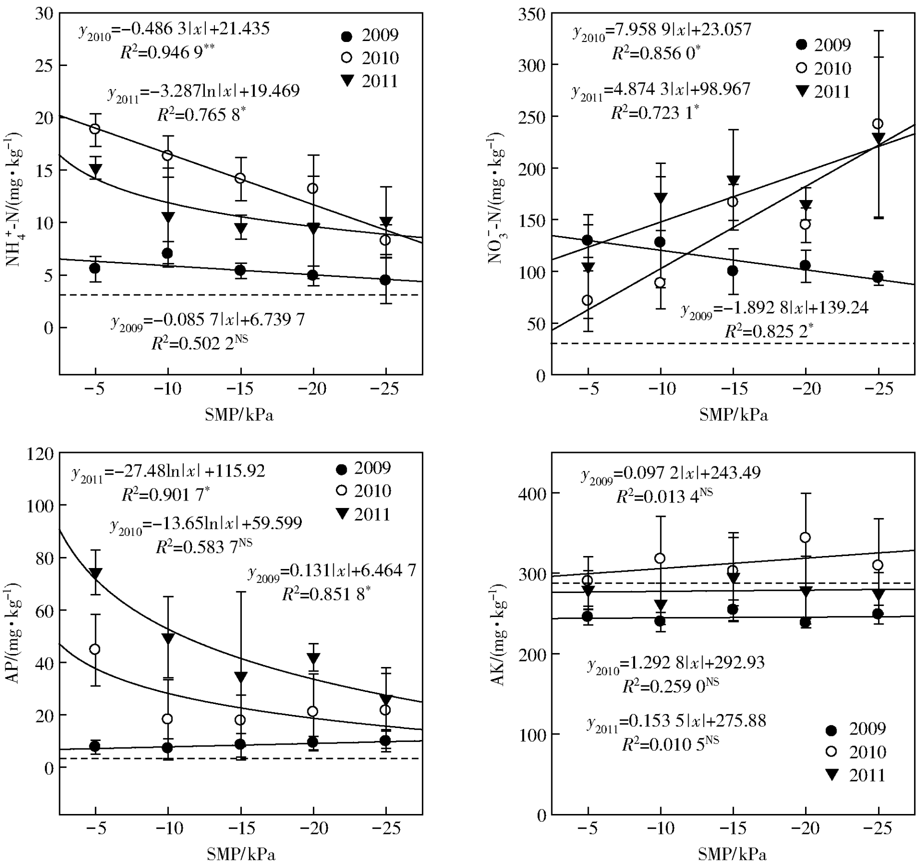


Fig. 8 Changes of soil ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (AP) and available potassium (AK) contents in root zone with soil-water matric potential (SMP) thresholds in different planting years

2.3 Growth and yield of *Lycium barbarum* L.

As a salt-tolerant plant, *Lycium barbarum* L. was planted widely in Ningxia. 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 got the highest value (81.1%) (Tab. 3). More applied water in S1 resulted in the deterioration of soil aeration conditions, causing a negative influence on the crop growth.

A wolfberry dry fruit yield of 45.0 ~ 56.8 kg/hm^2 was obtained in the first year, with no significant differences among treatments. The yield was increased significantly in the second year, and the yields of S1 and S2 were more than 450 kg/hm^2, which were higher than other treatments ($p < 0.05$). In the third year, the plant was gradually entering the full productive age. Non-significant difference ($p < 0.05$) was found among the dry fruit yields of S2, S3 and S4, which were around 900 kg/hm^2. This value was close to the level in local farmland and higher than those of S5 and S1 significantly, and S1 gave the lowest yield.

Tab. 3 Survival rates and dry fruit yield of *Lycium barbarum* L. in different planting years

Treatments	Survival rate/%			Dry fruit yield/(kg·hm^{-2})		
	2009	2010	2011	2009	2010	2011
S1	86.4^a	81.1^a	56.8^c	48.5 ± 10^a	465.8 ± 44.1^a	698.5 ± 49.0^c
S2	80.3^a	78.8^a	75.8^{ab}	54.2 ± 4.2^a	456.3 ± 29.1^a	908.8 ± 24.7^a
S3	83.3^a	81.8^a	81.1^a	45.0 ± 4.0^a	375.7 ± 14.6^b	865.7 ± 63.9^{ab}
S4	86.4^a	84.8^a	79.5^{ab}	56.8 ± 7.8^a	337.5 ± 31.7^c	863.7 ± 27.4^{ab}
S5	82.6^a	80.3^a	72.7^b	51.4 ± 16.0^a	395.1 ± 34.9^b	809.5 ± 62.9^b

3 Discussion

3.1 Infiltration of saline-sodic soil

In saline-sodic and sodic soil, sodicity alters soil physical properties directly, causing deterioration in soil structure because of increased swelling, dispersion and slaking upon wetting and increased crusting and hard-setting on drying, consequently a concomitant decline in permeability. The declined soil permeability restricts plant growth, and is also the primary problem to resolve during reclamation. On one hand, diffuse double layer theory of soil colloid is the reason of poor permeability in sodic soil[21-22]; and on the other hand, with the increase of sodicity and decreasing of salinity, the repulsive force between soil clays is increased, causing soil clay expanding and dispersion when the force arrives a certain level, consequently migration and deposition, and pore blocking. This is the leading cause of poor permeability of sodic soil[23]. In studied area, there is a large area of saline-sodic barren land up to now, and the small rainfall is ponding in the low-lying patches, lost only by the evaporation. Meanwhile, the pre-experiment showed that drip irrigation at a flow rate of less than 0.76 L/h quickly caused a saturated layer beneath the drip emitters, resulting in runoff from the ridge to the furrow. So when planting, sand-filled niches beneath drip emitters were adopted to redistribute the applied water. The specific purpose of sand-filled niche could be summarized as: firstly, to expand the water-soil contact area, thereby increasing the area over which infiltration of applied water occurs, and reducing the application rates to values that more closely matched the saturated hydraulic conductivity of the native soil; secondly, to provide a reservoir for holding the applied water before it is infiltrated; thirdly, to alleviate the stirring action of applied water on surface soil. The experiment results showed that the sand-filled niches under drip emitters facilitated soil infiltration of applied water, and soil water content was changed significantly in all layers (Fig. 2).

In the other words, since 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 inadequate to compensate for the effects of exchangeable sodium on clay swelling and dispersion. Soil hydraulic conductivityis decreased with increase of exchangeable sodium percentage and with decline of salt concentration of soil solution. Therefore, the soil EC_e/SAR_e ratio is an important indicator to reflect soil salinization and evaluate soil infiltration[24], so it should be attached more attention during the reclamation process of salt-affected soil. In uncultivated soil, the soil EC_e/SAR_e ratio was generally less than 0.2, except in 0 ~ 10 cm surface layer. This value would undoubtedly cause the reduction in soil infiltration[21]. The average values of EC_e in root zone at the end of three growing seasons were 6.2 ~ 8.3 dS/m, its corresponding SAR_e was 12.3 ~ 14.5 (mmol/L)$^{0.5}$, EC_e/SAR_e ratio was around 0.5. This means that the hydraulic conductivity of the soil in the root zone should not be reduced[19-20]. Consequently once the problem with infiltration rates at the soil surface due to a bad combination of EC_e and SAR_e is solved by the sand-filled niches beneath drip emitters, the hydraulic conductivity of the soil below the surface is not limited. Additionally, after SAR_e was reduced, the electrolyte concentration of irrigation water (*EC* was 2.1 dS/m) was expected to be sufficient, or at least helpful, for maintaining soil hydraulic conductivities in the vicinity of the emitter.

Since SAR_e is a close measure of exchangeable sodium percentage[16], a reduction in SAR_e means the exchangeable sodium was also decreased, requiring a source of Ca^{2+} to replace exchangeable Na^+. There are two sources of Ca^{2+}: the irrigation water and the dissolution of calcite presented in the soil. Calcite dissolution is enhanced by the increase of partial pressures of carbon dioxide in the soil due to microorganism and root respiration, and decomposition of organic matter[25].

3.2 Improvement of soil fertility

During the reclamation process of salt-affected soils, it is also worthy of attention to improve soil fertility and productivity besides leaching the excessive soluble salt. The soil available nutrients contents in root zone are directly related to the growth and yields of aboveground plants, and the soil productivity.

After planting, the accumulation of soil nitrogen in root zone was mainly caused by the application of urea with applied water. The increase in soil inorganic nitrogen in root zone facilitated the nutrients uptake by plant root[16]. Besides, the increased soil NO_3^--N also occurred in the surface layer of ridge slope and furrow due to the better mobility of soil NO_3^--N with water flow. This result was similar to the previous studies[26-28]. It was also found that after planting for three years, the *Lycium barbarun* L. entered the vigorous growth period, and the weeds began appearing in the furrow, the increasing plant litters and rhizosphere residues increased soil organic nitrogen, which was degraded into inorganic nitrogen by the simultaneously increased microbial activities. This should also be one of the reasons for the increased soil NH_4^+-N and NO_3^--N. Objectively, the accumulation of inorganic nitrogen (especially NO_3^--N) in the surface layer of ridge slope reflected partly the leaching loss of nitrogen nutrition. So for the nitrogen fertilizers management, it is suggested that the nitrogen fertilizer should be applied in the latter half period of an irrigation event to reduce the leaching of nitrogen and raise fertilizer use efficiency[29].

The soil P content is greatly influenced by soil parent materials, soil formation, tillage methods and fertilization[16]. The soil with low total P content generally lacks of AP, while the soil with high total P content, the AP is not necessarily sufficient for crop growth, due to that the most P exists in soil as insoluble phosphate. Like many soils developed from loess parent material and distributed widely in chief agricultural areas of China, takyric solonetz belongs to calcareous soil, the existing $CaCO_3$ absorbs many phosphorus as the form of calcium phosphate with slight solubility in water, consequently restricts the phosphorus availability[16,30]. The following facts should contribute to the increase in AP after planting. The formation of soluble phosphate, e. g. Na_3PO_4, after application of phosphoric acid, should be the main reason for the increased AP. Moreover, the mineralization of organic phosphorous and dissolution of difficult-soluble phosphorous compound with decline of soil pH value activated a part of unavailable P in soil. For example, the absorbed P by $CaCO_3$ was released into soil solution after the dissolution of original $CaCO_3$ because of the decline of soil pH value[31]. The results showed that the AP content in studied soil was relatively low, and it is necessary to apply phosphate fertilizer to meet the needs of crop growing.

The salt-affected soils in arid area, Northwest China, are generally rich in K[5], and the studied soil is no exception. This is because the main soil parent material is mica (illite), which is a favorable source of AK[2]. So during the reclamation, a small quantity of K fertilizer was applied. After planting for three years, the AK content in root zone was decreased slightly with the increasing demand of K for plant growth. Hence, when the plants enter vigorous growth stage, the demand of K is increased, it is necessary to supplement K fertilizer moderately.

3.3 Effects of SMP on plant growth

The results showed that high SMP was preferable for salt leaching and formation of low-salinity soil environment. This wasthe same to previous study, which reported that the suitable SMP for plant in high salinity environment was higher than that in nonsalinity[32]. The yields were higher under higher SMP thresholds ($-10 \sim -5$ kPa) than those under lower SMP thresholds. In the third year, with the plant stepping into mature and flourishing stage, the soil properties had already been considerably improved, the yields under SMP of $-20 \sim -10$ kPa were higher. The decrease of suitable SMP for crop growth during reclamation process were the same as previous studies in other salt-affected soils. Previous study also suggested that when SMP was controlled in the range of $-40 \sim -20$ kPa in normal soil, the soil moisture was suitable for crop growth[33-34]. And the yield response of *Lycium barbarum* L. in the third year to SMP was consistent with that of the same crop in nonsaline soils of Ningxia Plain, where an SMP of -20 kPa was recommended to trigger drip irrigation[35]. The above analysis shows that during the process of reclamation of highly salt-affected soil, soil environment was gradually ameliorated with the increase of planting years, and the suitable SMP for crop growth would be decreased. These changes of suitable SMP are the important characteristics of salt-affected soil reclamation.

4 Conclusion

For the highly saline-sodic wasteland of takyric solonetz spreads widely in Northwest China, a sand-filled niche beneath drip emitter could be adopted to improve soil water and salt regulation method and planting technology for cropping *Lycium barbarum* L.. The dissolved inorganic fertilizer was added with irrigation water. Besides improving soil infiltration significantly and leaching soil salt effectively, this pattern could also improve soil fertility and promote the crop growth. Considering the soil water-salt properties, soil nutrients distribution and growth of *Lycium barbarum* L., the SMP thresholds of -10 kPa in the first two years and -20 kPa from the third year were recommended to trigger drip irrigation for cropping *Lyciun barbarum* L. in this impermeable saline-sodic soil.

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doi:10.6041/j.issn.1000-1298.2016.10.019

浅层填沙滴灌种植枸杞改良龟裂碱土重度盐碱荒地研究

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摘要：龟裂碱土重度盐碱荒地主要分布在我国西北旱区，其土壤碱化度高、结构差、导水率低是制约其改良利用的关键因素。通过在滴头下方设置沙穴，探索在滴灌条件下种植枸杞的方式改良利用该盐碱荒地的可行性。通过设置 -5 kPa(S1)、-10 kPa(S2)、-15 kPa(S3)、-20 kPa(S4)和 -25 kPa(S5)5 个不同土壤基质势控制灌水下限处理，寻求最优的滴灌灌溉制度。结果表明，种植后土壤水分入渗性能得到显著改善，滴头下湿润区域面积不断增大，逐渐形成一个脱盐区（$EC_e<4$ dS/m）。控制较高的土壤基质势下限，有利于土壤盐分的淋洗。滴灌种植后土壤的 EC_e/SAR_e 显著增加，说明土壤盐分组成特征发生变化，土壤物理性质得到改善；土壤速效养分含量显著增加，其中硝态氮表现出较强的随水迁移性，存在淋失风险，而速效磷随水迁移性弱，主要积累在 0～20 cm 深度内。种植 3 a 之后，S1 成活率最低（56.8%），S3 最高（81.1%），而 S2、S3 和 S4 产量显著高于其他处理（$p<0.05$），三者之间差异不显著，均为 900 kg/hm^2 左右，达到当地良田水平。结合土壤水盐特征、养分分布及枸杞生长等各方面因素，可以通过在滴头下设置沙穴滴灌种植枸杞的方式改良龟裂碱土重度盐碱荒地，并在种植前 2 a 控制土壤基质势下限为 -10 kPa，从第 3 年改为 -20 kPa。

关键词：龟裂碱土；滴灌；水分调控；土壤基质势；盐分淋洗；枸杞

中图分类号：S156.4　　**文献标识码：**A　　**文章编号：**1000-1298(2016)10-0139-11

Amelioration of High Saline-sodic Wasteland of Takyric Solonetz by Cropping *Lycium barbarum* L. with Drip Irrigation and Shallow Sand-filled Niches

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Abstract: Takyric solonetz is spread mainly in arid area, Northwest China. Its poor soil structure and extremely low hydraulic conductivities ($K_s<0.1$ mm/d) are the key factors restricting its amelioration. The EC_e (electrical conductivity of saturated paste extract), SAR_e (sodium adsorption ratio of saturated paste extract), and pH_s (pH of saturated paste) of the native soil studied at depth of 0～30 cm were 12.30 dS/m, 44.12 $(\mathrm{mmol/L})^{0.5}$ and 9.33, respectively. After deep tillage, beds (1.0 m width, 0.5 m height) were formed. The drip lines were placed on beds covered with plastic. *Lycium barbarum* L. seedlings were then planted. A three-year field experiment was conducted to determine if reclamation could be achieved while cropping *Lycium barbarum* L. by using drip irrigation where soil beneath the drip

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收稿日期：2016-05-17　修回日期：2016-07-27

基金项目：国家高技术研究发展计划（863 计划）项目（2013AA102904）、国家自然科学基金青年科学基金项目（51509238、41503078）和中国科学院“西部之光”人才培养计划项目

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emitters near the plants was replaced with sand in niches that were 0.2 m ground diameter and 0.2 m depth. The purpose of sand-filled niche was to increase the area over which infiltration of water occured thereby reducing the application rates to values that more closely matched the saturated hydraulic conductivity of the native soil, provide a reservoir for holding the applied water before it infiltrated and avoid the adversely mechanical impact and the stirring action of applied water on soil surface. Five treatments based on soil matric potential (SMP) thresholds used to trigger drip irrigation were designed to find the optimal drip irrigation schedule, i. e., −5 kPa (S1), −10 kPa (S2), −15 kPa (S3), −20 kPa (S4) and −25 kPa (S5). The results showed that significant improvement was achieved in soil infiltration capability, which was demonstrated by the increasingly enlarged wetted area beneath the drip emitter. Consequently, a desalt region ($EC_e < 4$ dS/m) was formed, and high SMP level was favorable for the salt-leaching in soil. The ratio of EC_e/SAR_e was increased significantly after planting, which indicated the changes of soil salt composition characteristics and the amelioration of soil physical properties. After planting with drip irrigation, the contents of soil available nutrients were increased sharply. Nitrate nitrogen showed a high migration with water movement, and had potential to be lost by leaching, so nitrogen fertilizer should be applied in the later period during one irrigation event to reduce the leaching of nitrogen and raise fertilizer use efficiency. While available phosphorus was distributed mainly in depth of 0 ~ 20 cm under drip emitter, due to its low migration with water. After three years experiment, S1 had the lowest survival rate (56.8%), and S3 got the highest (81.1%), S2, S3 and S4 gave higher fruit yields than other treatments significantly ($p < 0.05$), which was around 900 kg/hm^2, and it was close to the level in local farmland. The findings indicated that a sand-filled niche beneath the drip emitter could be adopted for the reclamation of highly saline-sodic wasteland of takyric solonetz. Considering the factors, including soil water-salt properties, soil nutrients distribution and the growth of *Lycium barbarum* L., an SMP of −10 kPa in the first two years and −20 kPa from the third year could be used to trigger drip irrigation.

Key words: takyric solonetz; drip irrigation; water regulation; soil matric potential; salt leaching; *Lycium barbarum* L.

引言

盐碱地是我国重要的后备土地资源，盐碱地的合理开发利用对确保国家耕地面积不低于 18 亿亩的红线，和推动整个国民经济可持续发展具有重要战略意义[1]。相对于盐土，碱土和碱化度较高的盐碱土，通常由于土壤中过多钠离子的存在，导致土壤结构差，入渗率低，土壤盐分淋洗困难，改良难度较大[2-3]。改善土壤结构、提高入渗性能是改良利用此类碱化土壤首要解决的问题[4]。

龟裂碱土是分布在漠境或半漠境地区的一种碱化土壤，在我国主要分布在新疆、宁夏银川平原和内蒙古河套平原的西部[5]。在宁夏，龟裂碱土被当地群众俗称为白僵土，主要分布在平罗县的西大滩，面积约 2 万 hm^2，属于盐碱土纲碱土类盐渍龟裂碱土亚类[5-7]。龟裂碱土具有特殊的外部景观和剖面形态，一般不长高等植物，地面光秃，大面积分布的是地表似光板的重度盐碱荒地，仅在春夏季节短暂时期湿润，生长一些斑状的藻类或地衣，如微鞘藻，土壤环境恶劣。表层为厚约 1 cm 左右的灰色土结壳，结构易于散开，以下为块状或棱块状土层，整个剖面非常坚硬。该土壤与苏打盐碱土的区别在于：苏打盐碱土虽然也含有较多的苏打和较高的 pH 值，但苏打盐土没有碱土的剖面形态，而地下水矿化度低，地下水位也较碱土高[6,8]。最近几十年，当地尝试了多种方法进行该盐碱荒地的开垦，主要包括施用有机肥、勤灌勤排法种植水稻、加填客土及施用石膏等。然而，由于该土壤结构极差，导水性能极低（饱和导水率 $K_s < 0.1$ mm/d），多种方法并未见效，或由于较长的改良周期和较高的投入成本而难以推广应用[5,8-9]。

滴灌具有高频率、小流量、长时间的点源扩散特点，对土壤结构的破坏很小，可以在淋洗盐分的同时，保证养分供应，改善土壤通气性能，为作物根系提供一个适宜生长的土壤水、肥、盐环境[10]。土壤基质势（Soil − water matric potential，SMP）是表征土壤水分状况的理想指标，常被用来指导制定田间灌溉制度[11-12]。近年来，通过基于土壤基质势的盐碱地滴灌水盐调控方法，结合覆膜、垄作等农艺措施，

进行作物的种植，已在多个类型盐渍土的改良利用中取得成功，但其中多是入渗性能较好的盐土[13-15]。若能通过技术改进，将基于土壤基质势的滴灌水盐调控方法和作物种植技术，成功应用于龟裂碱土重度盐碱荒地，将有利于当地农业生产的发展和植被生态的修复，同时也为此类碱化土壤的利用提供技术指导。

为此，本文针对龟裂碱土重度盐碱荒地，通过在滴头下方设置沙穴，改进滴灌水盐调控方法和作物种植技术，探讨滴灌改良利用该盐碱荒地的可行性，并通过控制不同的土壤基质势下限，研究土壤水盐运移特征、养分分布状况及枸杞生长和产量，寻求最优的滴灌灌溉制度。

1　研究区域和方法

1.1　研究区概况

研究区位于龟裂碱土的典型分布区——宁夏平罗县西大滩（38°47′～38°57′N，106°20′～106°30′E，海拔高度 1 095 m），属于黄河中上游半干旱-半漠境盐渍区[5]。西大滩地处贺兰山东麓冲积平原和宁夏平原的过渡地带，属典型的干旱大陆性季风气候。年平均气温 9.4℃，多年平均降水量 178 mm，年蒸发量大于 2 000 mm。

研究区内平均地下水位约为 2.5 m，龟裂碱土土质均匀，地面光秃，无植被覆盖，为撂荒多年的重度盐碱荒地。剖面土壤结构紧实，10 cm 以下的土壤容重均在 1.5 g/cm^3 以上，0～30 cm 土壤平均饱和泥浆提取液电导率（EC_e）、饱和泥浆 pH 值（pH_s）和饱和泥浆提取液钠吸附比（SAR_e）分别为 12.30 dS/m、9.33 和 44.12 $(mmol/L)^{0.5}$。其他理化性质如表 1 所示。

1.2　试验设计与布置

1.2.1　种植方式

2009 年 4 月 23 日，对龟裂碱土盐碱荒地进行深翻，深度为 0.5 m，然后进行“半挖半填式”起垄，垄规格为垄高 0.5 m，垄肩宽 1.0 m，垄间距 3.0 m（图 1a）。考虑到该土壤极差的入渗性能，深翻起垄之后，在种植枸杞位置的滴头正下方设置一个半椭球体形状的沙穴（深 20 cm，地面直径 20 cm，体积约 4.2 L）（图 1a），其中填优质沙土。在沙穴内移栽枸杞幼苗（品种为“宁杞 1 号”），株距 1 m，每条垄上中间位置布置 1 条滴灌带，滴头间距 0.2 m。垄上覆膜（图 1a）。滴头工作压力设为 0.03 MPa，滴头流量为 0.76 L/h。灌溉水取自试验区周边的蓄水湖，灌溉水电导率（EC）、pH 值和钠吸附比（SAR）分别为 2.14 dS/m、8.87 和 6.02 $(mmol/L)^{0.5}$。

表 1　未种植土壤主要理化性质

Tab. 1　Main physicochemical properties of uncultivated soil

土层深度/cm	干容重/(g·cm^{-3})	EC_e/(dS·m^{-1})	pH_s 值	SAR_e/(mmol·L^{-1})$^{0.5}$	EC_e/SAR_e	速效养分质量比/(mg·kg^{-1})			
						NH_4^+-N	NO_3^--N	AP	AK
0～10	1.44	18.54	8.90	39.76	0.47	4.05	63.45	5.39	285.47
10～20	1.53	11.66	9.58	54.01	0.22	2.03	35.53	3.98	318.18
20～30	1.59	6.69	9.52	38.59	0.17	3.38	16.31	2.16	270.71
30～40	1.64	4.16	9.51	23.15	0.18	3.00	5.22	1.41	277.13
40～60	1.60	2.45	9.50	15.43	0.16	2.86	2.08	2.49	260.45
60～80	1.63	1.89	9.43	7.72	0.24	4.20	1.28	1.25	192.45
80～100	1.55	1.67	9.24	7.72	0.22	3.95	0.80	1.49	130.87

注：AP 为速效磷，AK 为速效钾。

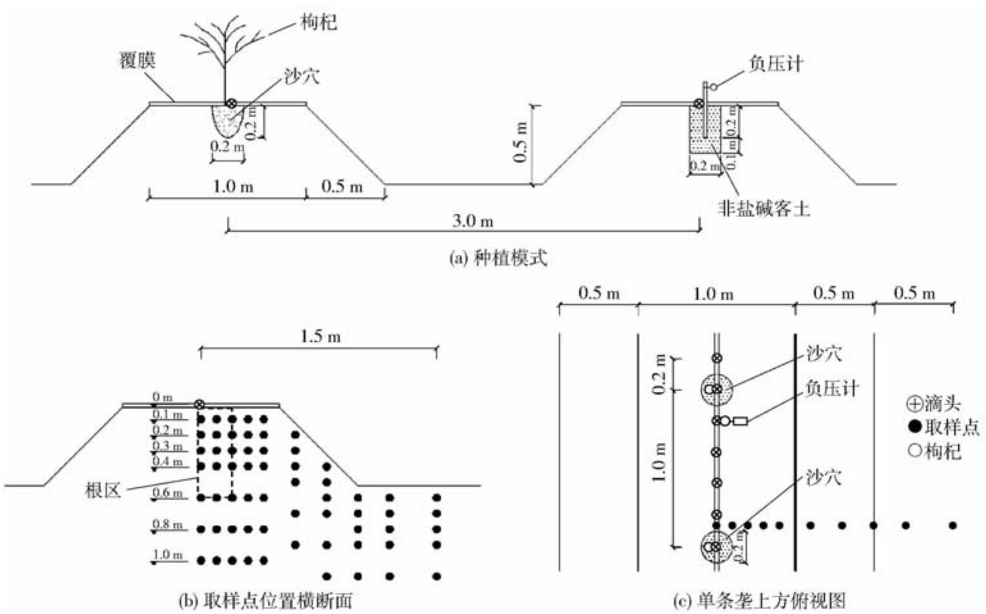
1.2.2　试验处理

试验设置 5 个土壤基质势处理，分别控制滴头正下方 20 cm 深度处土壤基质势下限为 −5 kPa（S1）、−10 kPa（S2）、−15 kPa（S3）、−20 kPa（S4）和 −25 kPa（S5），每处理设置 3 次重复，共 15 个小区，随机区组布置。小区尺寸为 12 m × 12 m，各小区包含 4 条垄。每个处理使用 1 个独立的滴灌系统，包括阀门、压力表、过滤器、施肥罐和 12 条滴灌带（每小区 4 条）等。

枸杞幼苗移栽之后，立即在约 3 d 的周期内灌水 20 mm，以降低表层土壤盐分，并提供足够的土壤水分，保证枸杞幼苗成活。待枸杞幼苗长势稳定后，开始执行基于土壤水基质势的灌水处理，一旦土壤基质势降至所设下限，立即灌水 5 mm，记录灌水次数和灌水量。在接下来的 2 a，分别于生长季初，灌水 10 mm，以淋洗在冬季因停止灌水、冻融交替、地表蒸发等因素有可能造成的积累于表层土壤中的盐分，之后的枸杞生育期内严格按照处理进行灌溉，具体灌溉情况如表 2 所示。

1.2.3　施肥和田间管理

尿素、磷酸和硝酸钾于每次灌水前添加于施肥罐中，加少量水溶解后随灌溉施入，所有处理施肥量



(a) 种植模式

(b) 取样点位置横断面

(c) 单条垄上方俯视图

图1　种植模式和取样点位置

Fig. 1　Planting pattern and soil sampling positions

表2　枸杞生长季内灌溉、降水、蒸发和施肥情况

Tab. 2　Irrigation, rainfall, evaporation and fertilization during growing seasons of *Lycium barbarum* L.

年份	处理	总灌水量/mm	灌溉频率/d	降水量/mm	蒸发量/mm	施肥量/(kg·hm^{-2})		
						N	P_2O_5	K_2O
2011(第1年)	S1	160	6.3	153.5	1 309.2	160	100	75
	S2	140	10.5					
	S3	130	15.8					
	S4	130	15.8					
	S5	125	21.0					
2012(第2年)	S1	220	4.2	150.3	1 475.1	300	150	100
	S2	180	5.2					
	S3	150	6.4					
	S4	125	7.7					
	S5	105	9.4					
2013(第3年)	S1	405	2.3	120.8	1 490.8	500	240	50
	S2	315	3.0					
	S3	280	3.3					
	S4	220	4.3					
	S5	190	5.0					

注:灌溉频率指处理期间2次灌溉之间相隔的平均天数;蒸发量指直径20 cm标准蒸发皿累计蒸发量。

一致(表2)。其他农艺措施,如剪枝、除草、杀虫等同周边高产农田。

在试验地的周边,设置排水沟(宽0.5 m,深0.5 m),以防止短时强降雨可能会产生的临时性淹涝和表层土壤的饱和。在试验过程中发现,排水沟内并没有形成大量、长时间的积水。种植垄、滴灌系统、种植作物及排水系统在3 a的试验期内保持不变。

1.3　土壤采样及分析

分别在种植枸杞的第1年(2009年)、第2年(2010年)和第3年(2011年)生长季末(10月中下旬),选择垂直于滴灌带的土壤剖面进行取土,剖面位置为种植沙穴外(图1c)。用土钻(直径4 cm,长20 cm)在每个剖面内采取土样62个。取土位置为与滴灌带水平距离0、10、20、30、40、60、80、100、120、150 cm处,深度为0～10 cm、10～20 cm、20～30 cm、30～40 cm、40～60 cm、60～80 cm和80～100 cm(图1b)。同时选择代表性土壤剖面利用环刀测定土壤干容重。

土壤剔除杂质后,立即取部分用105℃加热干燥法测定土壤质量含水率,然后利用实时的干容重数据计算土壤体积含水率。剩余土样风干,过1 mm

筛，装入密闭自封袋，室温下 8 周内测定。

土壤盐分性质采用调制饱和泥浆的方法进行。20 g 土样加少量水经过夜浸泡，然后调制成饱和泥浆。pH_s用 pH 计（PHS－3C，上海精密科学仪器有限公司）测定。然后饱和泥浆经离心（4 000 r/min，30 min）获得提取液，用于测定 EC_e和 Ca^{2+}、Mg^{2+}及 Na^+浓度。EC_e用电导率仪（DDS－11A，上海精密科学仪器有限公司）测定，Ca^{2+}和 Mg^{2+}浓度用 EDTA 滴定法测定，Na^+用火焰光度计法测定。SAR_e计算式为

$$SAR_e=\frac{C_{Na^+}}{(C_{Ca^{2+}}+C_{Mg^{2+}})^{0.5}} \tag{1}$$

式中　C_{Na^+}、$C_{Ca^{2+}}$、$C_{Mg^{2+}}$——饱和泥浆提取液中 Na^+、Ca^{2+}、Mg^{2+}浓度，mmol/L

土壤铵态氮和硝态氮含量由分光光度计测定，速效磷由钼锑抗法测定，速效钾由火焰光度计测定[16]。

1.4　数据分析

将与滴头水平距离 0～20 cm 和深度 0～60 cm 范围定义为根区（图 1b），根区土壤性质由区域内取样点数值加权平均法计算得出。数据分析采用 Excel 2010 和 SPSS 16.0 统计软件进行，绘图由 Surfer 8.0 和 SigmaPlot 10.0 完成。

2　结果与分析

2.1　土壤水盐特征

2.1.1　剖面土壤水分运移

图 2 为 S3 处理下不同种植年限土壤剖面内体积含水率分布情况。从图中可以看出，滴灌种植之后，在滴头下方形成一个湿润区，体积含水率均达到 0.34 cm^3/cm^3以上。随着滴灌种植年限的延长，滴头下的湿润区域在深度和水平方向逐渐扩展，说明土壤入渗性能得到显著改善。在垄坡和垄沟的表层，由于无覆盖，土面蒸发强烈，土壤含水率较低。

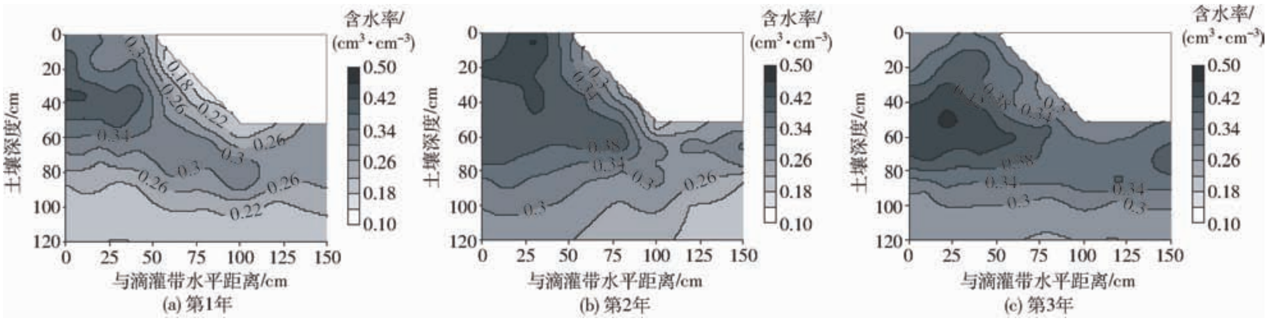


图 2　S3 处理下不同种植年限枸杞生长季末土壤剖面体积含水率分布

Fig. 2　Spatial distributions of soil volumetric moisture content in soil transects at end of growing seasons of *Lycium barbarum* L. in different planting years under S3

其他处理下土壤水分运移呈现相同趋势，处理差异主要表现在滴头下方的根区范围内。图 3 为不同种植年限下，根区土壤体积含水率随土壤基质势控制下限的变化，图中数值为加权平均值（ * 和 ** 分别表示在 $p<0.05$ 和 $p<0.01$ 水平上显著，NS 代表不显著，下同）。年限之间比较发现，种植 1 a 的根区土壤体积含水率低于种植 2 a 和 3 a 的水平，后二者之间差异不显著。控制土壤基质势水平均高于 －15 kPa 的 S1、S2、S3 处理，种植 2 a 后，根区土壤含水率均在 0.40 cm^3/cm^3以上，接近饱和状态（该土壤 0～60 cm 平均饱和含水率 θ_s为 0.45 cm^3/cm^3）。随基质势控制下限的降低（负值绝对值增大），根区土壤含水率逐渐减小，3 a 内呈现相似的显著性直线关系（$p<0.01$）。

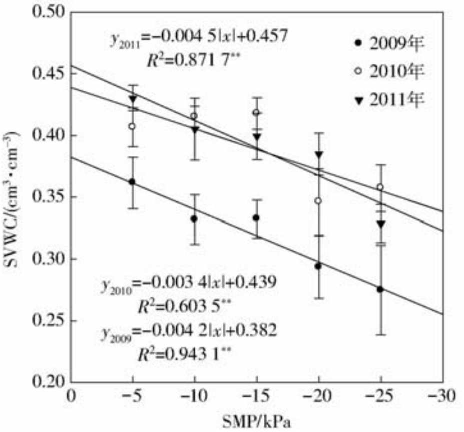


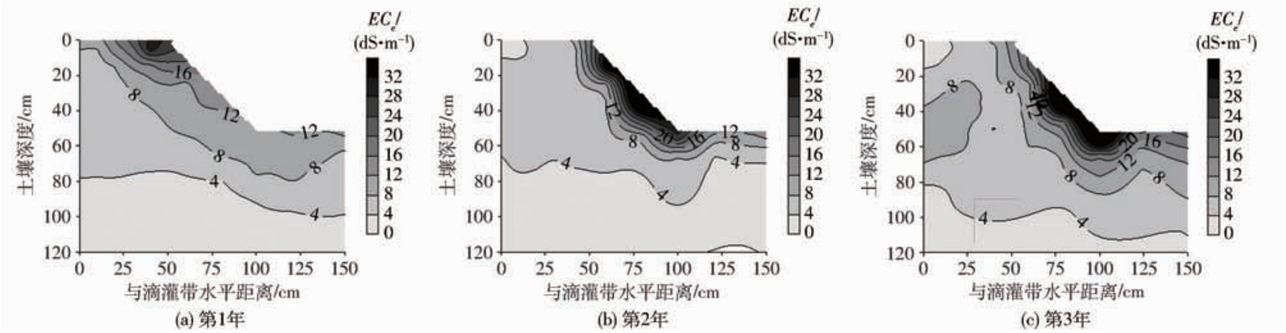
图 3　不同种植年限下根区土壤平均体积含水率（SVMC）随土壤基质势（SMP）下限的变化

Fig. 3　Changes of average soil volumetric moisture content (SVMC) in root zone with different soil matric potential (SMP) thresholds in different planting years

2.1.2　根区土壤盐分淋洗

随着土壤水分的运移，不同年限土壤盐分（EC_e）在剖面内的分布状况（以 S3 为例）如图 4 所示。滴灌种植之后，在滴头下方形成一个脱盐区（$EC_e<4$ dS/m），土壤盐分更倾向于分布于湿润体的边缘。随着种植年限的增加，滴头下的脱盐区面积逐渐增加。就整个剖面而言，除了少部分盐

分向下层土壤中运移以外,土壤中的大分部盐分逐渐积累在垄坡和垄沟的上层土壤中,这是因为滴灌的淋洗、垄坡和垄沟位置土面无覆盖、蒸发强烈的缘故。



(a) 第1年 (b) 第2年 (c) 第3年

图4 S3处理下不同种植年枸杞生长季末土壤EC_e在剖面中的分布

Fig. 4 Spatial distributions of soil EC_e in soil transects at end of growing seasons of *Lycium barbarum* L. in different planting years under S3

和土壤水分相似,不同基质势水平对土壤盐分淋洗的处理差异主要体现在根区范围内(图5,不同小写字母表示在$p<0.05$水平上差异显著,黑色虚线为种植前的初始值,下同)。滴灌种植3 a后,维持较高土壤基质势的S1(-5 kPa)处理,根区土壤EC_e最低,为3.26 dS/m,已经低于盐渍土定义中的阈值(4 dS/m)[4]。随土壤基质势控制下限的降低,根区土壤含盐量逐渐升高,S5根区土壤EC_e为9.19 dS/m,但仍显著低于种植前水平。和初始值相比,S1~S5处理下,根区土壤EC_e降低率分别为68.16%、39.45%、26.56%、25.14%和10.40%。说明随着土壤水分的运移,根区土壤盐分得到有效淋洗,且控制较高的土壤基质势水平,有利于土壤盐分的淋洗。

随着土壤盐分的淋洗,根区土壤SAR_e也降低,且相对降低幅度较EC_e更大,这是因为SAR近似反映土壤交换性钠百分比(Exchangeable sodium percentage,ESP)[17],该碱性土壤盐分阳离子主要以Na^+为主[18],而相对于Ca^{2+}、Mg^{2+}等其他离子,Na^+被土壤粘粒的吸附力较小,随水迁移性更强[3]。种植3 a之后,所有处理的根区土壤SAR_e均降低至20(mmol/L)$^{0.5}$以下,降低幅度均在50%以上,其中S1最低,为9.59 (mmol/L)$^{0.5}$,已低于碱土定义中SAR_e大于13 (mmol/L)$^{0.5}$的阈值[4],较初始值降低75.32%,S5最高,为18.44 (mmol/L)$^{0.5}$,降低率为52.56%。

滴灌种植3 a之后,根区土壤pH_s值显著降低,其中S1降低幅度最大,为7.9,较初始值的降低幅度为15.30%,S2和S3下,根区土壤pH_s值分别为8.4和8.5,降低幅度分别为10.17%和8.32%。以上3个处理下种植3 a的根区土壤pH_s值已经低于碱土pH值的阈值(8.5)[7]。由于土壤自身缓冲性,短时间尺度上,土壤pH值不可能像盐分一样,出现较大幅度变化。

2.1.3 土壤EC_e/SAR_e

初始土壤中,剖面内土壤EC_e/SAR_e仅在0.2~0.4之间(表1),这势必对土壤物理性质产生不利影响[19-20]。滴灌种植3 a之后的,不同基质势水平处理土壤EC_e/SAR_e在剖面内的分布如图6所示。滴灌种植之后,土壤EC_e/SAR_e显著增加,特别是在滴头下方的区域范围内,说明随着土壤盐分的淋洗,盐分组成特征也发生变化,根区土壤物理性质得到改善[20]。维持较高土壤基质势水平的S1,盐分淋洗效果最好,其根区土壤EC_e/SAR_e也较大,滴头下

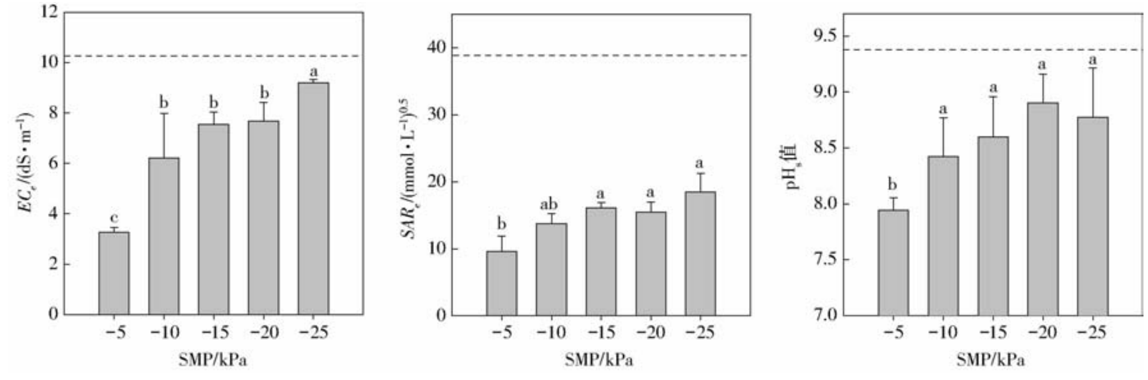
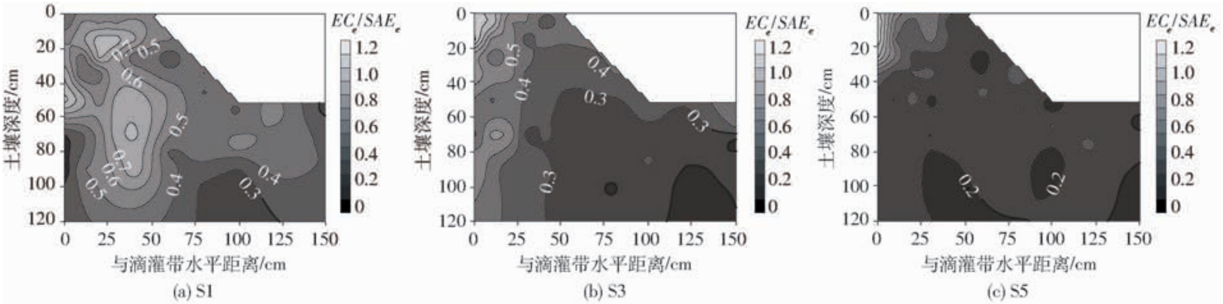


图5 种植3 a后不同土壤基质势(SMP)处理下根区土壤盐分特征

Fig. 5 Soil salt properties in root zone under different soil matric potential (SMP) treatments after three planting years

方土壤 EC_e/SAR_e 普遍达到 0.7 以上。随着基质势控制水平的降低，土壤 EC_e/SAR_e 增大的区域面积逐渐减小（图 6）。



(a) S1　(b) S3　(c) S5

图 6　滴灌种植 3 a 之后不同土壤水基质势处理土壤剖面 EC_e/SAR_e 分布

Fig. 6　Spatial distributions of soil EC_e/SAR_e ratio in soil transects after three planting years under different SMP treatments

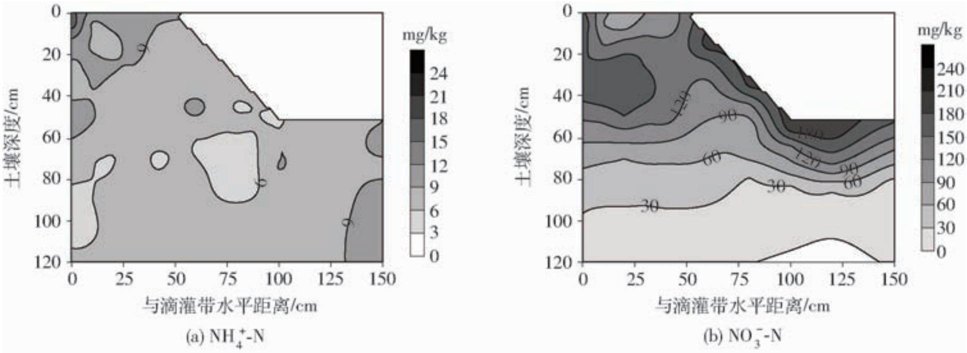
2.2　土壤养分状况

未种植土壤中铵态氮、硝态氮和速效磷含量较低。在碱性环境中，NH_4^+ 容易以 NH_3 的形式挥发，该土壤铵态氮含量初始值仅在 2.86 ~ 4.20 mg/kg 之间（表 1）。滴灌种植 3 a 之后，土壤中的铵态氮含量明显增加，根区范围内土壤铵态氮含量达到 9 mg/kg 以上（图 7）。

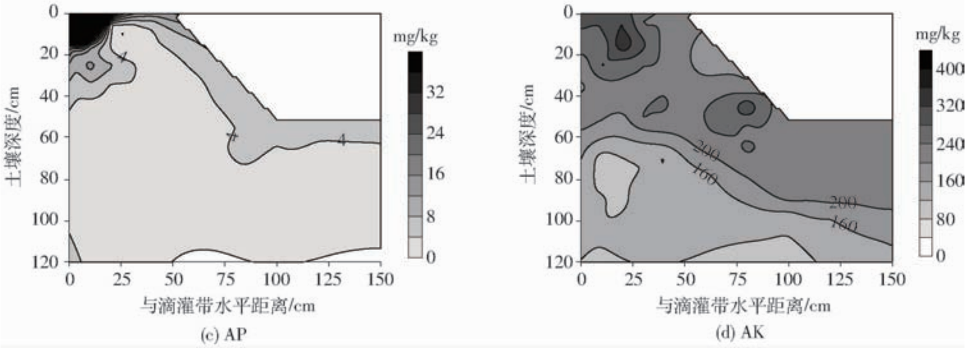
未种植的 0 ~ 100 cm 原状土剖面中，硝态氮含量随土壤深度的增加而减小，从表层的 63.45 mg/kg 降低至 90 ~ 100 cm 深度处的 0.80 mg/kg（表 1），0 ~ 40 cm 深度平均值为 30.13 mg/kg。滴灌种植之后土壤硝态氮含量明显增加，整个根区土壤硝态氮含量普遍在 60 mg/kg 以上（图 7）。就整体剖面内的分布而言，土壤硝态氮有 2 个明显的积累区域，一是滴头正下方的根系区域，二是垄坡的表层，土壤硝态氮含量普遍在 100 mg/kg 之上。

未种植的原状土速效磷含量为 1.25 ~ 5.39 mg/kg，且随土壤深度的增加而降低（表 1）。0 ~ 40 cm 深度土壤速效磷含量为 3.24 mg/kg。滴灌种植 3 a 之后，土壤速效磷含量显著增加，但由于速效磷随水迁移性弱[16]，主要积累在滴头下 0 ~ 20 cm 小范围区域内。

未种植的原状龟裂碱土中速效钾含量较高，在 130.87 ~ 318.18 mg/kg 之间，随土壤深度的增加含量逐渐降低。在本试验中，仅施入了少量的钾肥。滴灌种植 3 a 之后，土壤速效钾含量和种植前差异



(a) NH_4^+-N　(b) NO_3^--N



(c) AP　(d) AK

图 7　滴灌种植 3 a 后 S3 处理下土壤铵态氮（NH_4^+-N）、硝态氮（NO_3^--N）、速效磷（AP）和速效钾（AK）在剖面中的分布

Fig. 7　Spatial distributions of soil ammonium nitrogen（NH_4^+-N），nitrate nitrogen（NO_3^--N），available phosphorus（AP）and available potassium（AK）in soil transects after three planting years under S3

不大，在 200 mg/kg 左右，仍处于较高钾素水平。

滴灌种植之后，根区土壤平均速效养分含量与土壤基质势控制下限之间的关系如图 8 所示。种植 1 a 根区土壤铵态氮含量较种植前略有增加，但处理之间差异不显著，种植 2 a 和 3 a 之后，根区土壤铵态氮含量显著增加，且随土壤基质势下限的降低，铵态氮含量逐渐降低，分别呈显著的直线和对数关系（$p<0.05$）。

滴灌种植之后，根区土壤硝态氮含量较初始值显著增加。种植 1 a 之后的根区土壤硝态氮含量随基质势下限的降低而降低，但处理之间的差异较小。种植 2 a 和 3 a 之后，根区土壤硝态氮含量变化趋势一致，但与种植 1 a 的结果相反：随基质势下限的降低而显著增大（$p<0.05$）。这可能是因为随着枸杞树龄的增加，施肥量增多，而维持较低土壤基质势的处理（如 S5），由于灌水次数较少，单次施肥量大幅增多，从而使更多氮肥集中在滴头下方。

随着种植年限的增多，根区土壤速效磷含量逐渐增多。随土壤基质势水平的降低，速效磷含量呈对数式逐渐减小的趋势，S1 处理最高。这是由于速效磷随水迁移性弱，维持较高基质势的处理灌水次数较多，有利于更多磷酸根离子均匀分布于根区内。由于种植过程中施钾量较少，土壤中速效钾含量变化不大，各处理之间差异不显著。

总体来看，滴灌种植 1 a 的枸杞根区土壤速效养分含量相对较低，且各处理之间差异较小，种植 2 a 之后土壤速效养分含量显著增加，各处理之间的差异也增大。

2.3 枸杞生长及产量

作为一种较耐盐植物，枸杞在宁夏平原广泛种植。种植第 1 年的统计结果显示，各处理的平均成活率达到 83.8%，种植 3 a 之后，S1 处理的成活率最低，仅有 56.8%，S3 处理最高，为 81.1%（表 3）。在 S1 处理下，维持较高的土壤水基质势导致土壤长期处于近饱和状态，土壤通气状况恶化，影响根系呼吸，从而对作物生长造成不利影响。

枸杞在种植第 1 年即形成了一定的产量，干果产量在 45.0 ~ 56.8 kg/hm^2 之间，各处理间差异不大。第 2 年，S1 和 S2 处理枸杞干果产量达 450 kg/hm^2，显著高于其他处理（$p<0.05$）。第 3 年，枸杞逐渐进入盛果树龄，S2、S3 和 S4 处理产量较高，达 900 kg/hm^2 左右，已达到当地良田水平，三者之间差异不显著，且显著高于 S5 和 S1 处理（$p<0.05$），S1 处理最低。

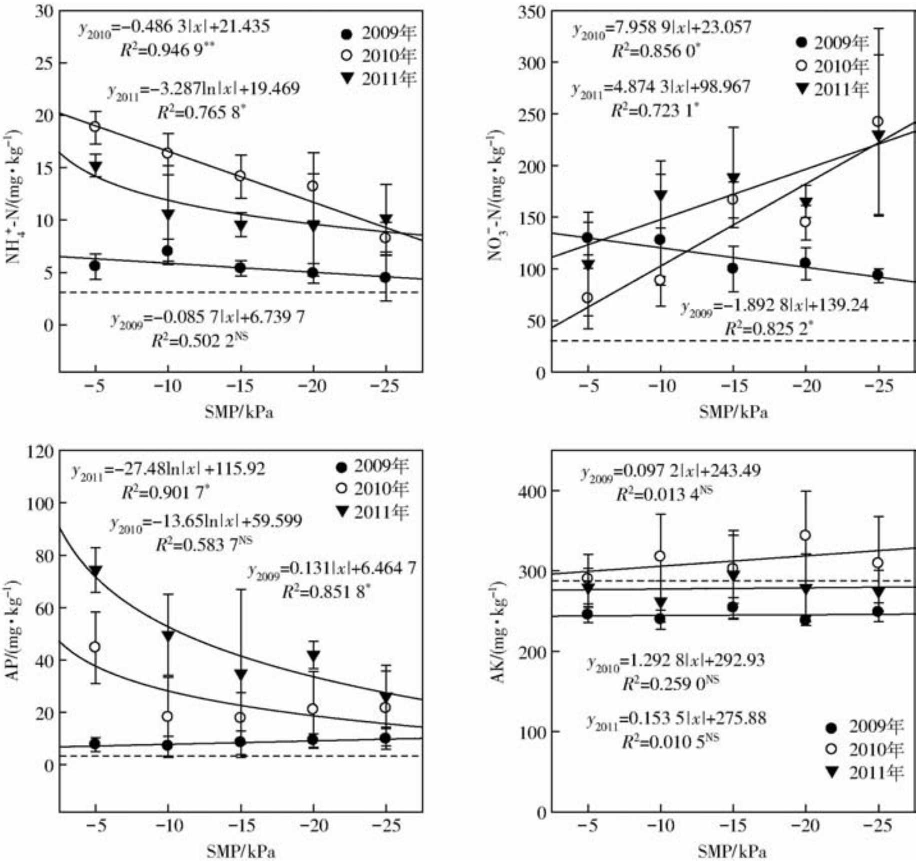


图 8 不同种植年限根区土壤铵态氮（NH_4^+-N）、硝态氮（NO_3^--N）、速效磷（AP）、速效钾（AK）含量随土壤水基质势（SMP）控制下限的变化

Fig. 8 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 soil-water matric potential（SMP）thresholds in different planting years

表 3　不同种植年限枸杞成活率和干果产量

Tab. 3　Survival rates and dry fruit yield of *Lycium barbarum* L. in different planting years

处理	成活率/%			干果产量/(kg·hm^{-2})		
	2009 年	2010 年	2011 年	2009 年	2010 年	2011 年
S1	86.4^{a}	81.1^{a}	56.8^{c}	48.5 ± 10^{a}	465.8 ± 44.1^{a}	698.5 ± 49.0^{c}
S2	80.3^{a}	78.8^{a}	75.8^{ab}	54.2 ± 4.2^{a}	456.3 ± 29.1^{a}	908.8 ± 24.7^{a}
S3	83.3^{a}	81.8^{a}	81.1^{a}	45.0 ± 4.0^{a}	375.7 ± 14.6^{b}	865.7 ± 63.9^{ab}
S4	86.4^{a}	84.8^{a}	79.5^{ab}	56.8 ± 7.8^{a}	337.5 ± 31.7^{c}	863.7 ± 27.4^{ab}
S5	82.6^{a}	80.3^{a}	72.7^{b}	51.4 ± 16.0^{a}	395.1 ± 34.9^{b}	809.5 ± 62.9^{b}

3　讨论

3.1　碱化土壤的入渗问题

在部分盐碱土和碱土中，过量的交换性 Na^+ 和相对较低的含盐量，恶化了土壤物理性质，土壤入渗性能差，不渗水，不透气，是限制植物生长的主要原因，也是此类盐碱地的改良利用中首要解决的问题。一方面，土壤胶体的扩散双电层理论是碱化土壤渗透性能差的原因[21-22]；另一方面，随着碱化度的升高和含盐量的降低，土壤颗粒之间的排斥力增加，增加到一定程度之后，土壤粘粒开始膨胀、分散，之后运移和沉积，堵塞土壤空隙，这是碱化土壤渗透性能差的主要原因[23]。所以，研究区龟裂碱土至今仍多是寸草不生的荒地，少量降水也长期存留在低洼区域，基本靠蒸发损失，说明土壤入渗性能极差。同时笔者在前期预试验中发现，即使在滴头流量小于 0.76 L/h 的滴灌条件下，灌溉水仍无法良好地入渗，很快在土壤表层形成径流。因此，所以在种植利用过程中，在种植枸杞的滴头正下方设置沙穴，对灌溉水进行“二次分配”：首先，沙穴能够扩大水-土接触面，增加灌溉水的入渗面积，进一步降低灌溉水的供应速率，使其更加接近该土壤的饱和导水率；其次，沙穴还能够暂时存储未入渗的水分，延长入渗时间，促进土壤入渗；再次，沙穴的设置，还避免了灌溉时水滴的击打对表层原始土壤结构的破坏。研究结果显示，在“滴灌 + 沙穴”的共同作用下，土壤入渗性能得到显著改善(图 2)。

“低盐高碱”的特征是造成盐碱土和碱土结构恶化、入渗性能降低的主要原因。随交换性 Na^+ 含量的增加和含盐量的减小，土壤导水率降低。所以 *EC*/*SAR* 是表述土壤盐碱化特征、衡量土壤入渗性能的主要指标[24]，在盐碱土，特别是碱土的利用过程中，需要得到重视。种植前的原始土壤中，除表层 0 ~ 10 cm 之外，EC_e/SAR_e 普遍小于 0.2，势必造成土壤入渗性能的恶化[21]，导致土壤饱和导水率极低。滴灌种植之后，统计连续 3 a 的数据发现，不同处理根区土壤平均 EC_e 在 6.2 ~ 8.3 dS/m 之间，与此对应的 SAR_e 水平是 12.3 ~ 14.5 $(mmol/L)^{0.5}$，EC_e/SAR_e 在 0.5 左右，这意味着在此环境下，根区土壤导水率不会降低[19,20]。也就是说，一旦该土壤的入渗问题在“滴灌 + 沙穴”的共同作用下得到解决，土壤盐分组成特征发生变化，下层土壤的入渗性能将不再是限制其利用的关键因素。与此同时，待 SAR_e 降低之后，灌溉水的电解质浓度($EC = 2.1$ dS/m)在维持滴头周边土壤的导水性能方面是有利的。

另外，由于 SAR_e 的降低反映的是交换性钠离子的减少[16]，这就需要更多的 Ca^{2+} 来取代交换性 Na^+。本研究中有 2 个 Ca^{2+} 的来源：一是灌溉水，二是土壤中原有 $CaCO_3$ 的溶解。在种植作物条件下，土壤微生物和根系的呼吸，以及有机质的降解，可以产生 CO_2，增加土壤的 CO_2 分压，从而促进土壤中 $CaCO_3$ 等含钙矿物的溶解[25]。

3.2　盐碱荒地土壤肥力的提升

在盐碱地的改良利用过程中，除了需要淋洗过量的盐分以外，还需要注意培肥土壤，提高土壤生产力。根区土壤速效养分的丰缺程度直接关系到农作物的生长状况和产量水平。

滴灌种植过程中，尿素随灌水由滴头施入土壤，从而在滴头下方形成氮肥的积累区。此区域土壤无机氮含量的增加有利于植物根系的吸收利用[16]。此外，硝态氮表现出了较强的随水迁移性，易随水分运移至垄坡和垄沟的表层土壤中，这与前人研究结论类似[26-28]。此外，试验过程中还发现，种植的第 3 年，随着土壤理化性质的改良，垄坡和垄沟中开始出现杂草，其凋落物有助于该区域土壤有机氮含量的增加，进而被活性增强的土壤微生物转化为无机氮。这可能也是该区域铵态氮和硝态氮增加的原因之一。但客观地说，土壤硝态氮在垄坡和垄沟表层土壤中的积累，反映的是部分养分的淋失和浪费。因此，在肥料管理中，应将氮肥的施用置于滴灌灌水时间段的后半期，并尽量减少单次施入量，以减轻氮肥随水淋洗出根区范围，提高氮肥利用率[29]。

土壤中全磷含量受土壤母质、成土作用和耕作、施肥的影响很大[16]。在全磷含量很低的情况下，土

壤速效磷的供应常不足,但是全磷含量较高的土壤,却未必说明其含有足够的速效磷供应当季作物生长的需要,因为土壤中的大部分磷以难溶性化合物的形式存在。例如我国大面积分布的、发育于黄土母质的石灰性土壤中,由于大量游离 $CaCO_3$的存在,大部分磷成为难溶性的磷酸钙盐,能被植物吸收利用的速效磷含量很低[16,30],本研究中的龟裂碱土就属于这种类型土壤。因此,本研究土壤中增加的速效磷可能有 2 部分来源,一是施入磷酸之后,Na_3PO_4等可溶性磷酸盐的形成,这应该是速效磷增加的主要原因;二是植物在生长过程中根系会分泌一些低分子有机酸等物质,对土壤中的磷具有一定的活化作用,而且施入的氮肥本身的生理酸性也促进了磷酸盐的溶解和释放,土壤中速效磷含量有所增加[31]。研究发现在改良利用的前 2 a,龟裂碱土土壤中速效磷含量较低,有必要增施磷肥来满足作物生长的需要。

旱区盐渍化土壤普遍富钾[5],龟裂碱土也不例外。这是因为与很多碱土一样,该土壤的主要粘土矿物为云母(伊利石),是植物速效钾的良好供应库[2],所以在开发利用过程中,仅施入了少量的钾肥。种植 3 a 之后,随植物生长所需钾素的增多,根区土壤速效钾含量略有降低。因此,待植物生长旺盛、对钾素的需求增多之后,应注意补施钾肥。

3.3 不同土壤基质势水平对作物生长的影响

本研究结果显示,维持较高的土壤基质势水平有利于盐分的淋洗和根区土壤低盐环境的形成,这与前人研究结果类似,焦艳平等[32]指出,在土壤含盐量较高的情况下,适宜作物生长的土壤基质势水平要比一般土壤显著提高[32]。所以本研究中,在种植的第 1 年和第 2 年,土壤基质势控制在 -10 kPa 以上时(S1 和 S2 处理),枸杞的产量较高。而在种植 3 a 之后,土壤水盐环境已得到显著改善,土壤基质势控制在 -20 kPa 以上时,枸杞产量最高,这与其他地区作物在非盐碱地土壤上的规律类似。前人研究结果指出,对于一般类型的土壤和作物而言,土壤基质势控制在 -40 ~ -20 kPa 之间,土壤水分状况比较适合于作物生长[33-34]。另外,贾俊姝等[35]在宁夏平原非盐碱地上的研究指出,可以通过控制土壤基质势高于 -20 kPa 来指导枸杞的滴灌灌溉[35]。以上分析说明,随着种植年限的增加,土壤环境将向有利于作物生长的方向转化,适宜作物生长的土壤基质势水平也会随之降低,这种变化过程是重度盐碱荒地利用过程中的重要特征。

4 结束语

对于我国西北地区广泛分布的龟裂碱土重度盐碱荒地,可以采用在滴头下设置沙穴的方式,改进滴灌水盐调控方法和作物种植技术,进行枸杞的种植,无机肥料溶于水后随灌水施入。该方式在显著改善土壤入渗性能、有效淋洗盐分的同时,还可以提升土壤肥力,促进枸杞生长。综合考虑土壤水盐特征、养分分布及作物生长等各方面因素,可以以种植前 2 a 控制土壤水基质势下限为 -10 kPa,从第 3 年改为 -20 kPa 的方式来指导滴灌灌溉。

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