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Soil water and salinity dynamics under the improved drip-irrigation scheduling for ecological restoration in the saline area of Yellow River basin

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ABSTRACT

The drip-irrigation scheduled by different soil matric potential (SMP) thresholds at different stages according to soil water and salt management purposes was usually adopted for revegetation in saline-alkali land. To reveal the desalinization mechanism of this multi-stage drip-irrigation scheduling, a 3-year field trial, adopting this method for revegetation, was conducted in an arid saline area. The trial consisted of 5 irrigation treatments marked S1-S5, with their SMP that monitored directly under drip emitter at 0.2 m depth correspondingly controlled higher than − 5, − 10, − 15, − 20 and − 25 kPa. Results showed the SMP threshold of − 5 kPa during the unified irrigation stage induced a leaching fraction (LF) of 42.6% and a minimum recharge amount (MRA) from groundwater of zero, thus resulting the relative desalinization rate (RDR) of 91.8% in 0–120 cm soil layer. When treatment applied, the average electrical conductivity of the saturated soil extracts (ECe) in 0–40 cm among three growing seasons in S1-S5 treatments linearly increased from 0.90 to 1.73 dS/m as SMP threshold decreased from − 5 to − 25 kPa, resulting from the LF correspondingly decreasing from 18.4% to 2.5% and the MRA increasing from 0 to 21.4 mm. The inter-annual salt dynamic indicated a salt equilibrium state was formed in 80–120 cm soil layer when the SMP threshold was set higher than − 10 kPa and that was formed in 40–80 cm soil layer if the SMP threshold was set between − 20 and − 15 kPa. This study found the SMP threshold controlled the LF and MRA, and eventually determined the dynamics of soil salinity, which explained the efficient desalinization mechanism under the multi-stage drip-irrigation scheduling. A key SMP threshold of − 5 kPa for rapid soil leaching stage and that of − 20 kPa for precise salt regulating stage were recommended for vegetation construction in the low-lying saline area.

1. Introduction

The problem of soil salinization is ever increasing, due to poor irrigation and drainage practices in some semi-arid and arid zones with high evapotranspiration rates and high watertable (Munns, 2002, 2005). In these areas, salinization occurs due to the upward movement and evaporation of saline groundwater when the groundwater depth is within 2 m (White, 2006). The Yinchuan plain, distributed along both sides of the Yellow River, is one of the most ancient irrigated areas in China and is deeply troubled by the soil salinization. On the one hand, the abundant flooding irrigation water maintains the agricultural prosperity for over 2000 years, however, on the other hand, the watertable is raised and salinity is increased in some low-lying edges of the plain due to the large amounts of drainage (Wang et al., 1993; Xiong et al., 1996). Reducing the soil salinity, and lowering the watertable by proper practices, are important issues in the similar low-lying areas all over the world.

Drip irrigation applies water precisely and uniformly at high frequencies, reduces drainage through precise irrigation scheduling and maintains high soil water potential to facilitate water uptake by the plant roots, being the most efficient irrigation method for reclaiming salt-affected soils (Goldberg et al., 1976; Hanson et al., 2009; Kang, 1998; Wan et al., 2007). The drip-irrigation scheduled by tensiometer is worldwide adopted for the cultivation of crops and vegetables, because

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it is precise in monitoring the soil matric potential (SMP) that directly related to the water uptake by plant root and is also convenient for the field operation (Kang et al., 2004; Klein, 2004; Phene et al., 1989). Tensiometers buried at a depth of 20 cm exactly under drip emitters for the annual plant and depths of both 20 and 50 cm for the perennial plant are efficient for the water and salt management when applied to saline soil reclamation (Kang et al., 2012, 2004; Wan et al., 2012).

Using this drip-irrigation scheduling method, studies have found that soil environment improved a lot in 2–3 years. In a semi-humid area in northeast China, Liu et al. (2011) conducted a 2-year field experiment for a perennial pasture cultivation under SMP initiated drip-irrigation in heavily soda saline-alkali soil, in which they found that the highest salt leaching efficiency occurred when SMP higher than − 10 kPa after 2 years. The drip-irrigation combined with a gravel–sand layer was effective to construct vegetation during the reclamation of coastal saline-alkali soil and the SMP higher than − 5 kPa was recommended for drip-irrigation scheduling during first 3 years (Sun et al., 2012). In recent years, the multi-stage drip-irrigation for perennial vegetation construction in saline soil has been proved efficient. For example, Chen et al. (2015) came up with a three-stage drip-irrigation scheduling for *Rosa chinensis* cultivation in the coastal saline soil based on the salt leaching process and plant response, in which the SMP thresholds of − 5 kPa, − 10 kPa and − 20 kPa for the first, the second and the third year, respectively, were recommended for triggering irrigation. Based on a 3-year field experiment, Dong et al. (2021) also suggested the SMP thresholds of − 5 kPa, − 10 kPa and − 20 kPa for the first 3 years were very helpful for leaching and controlling soil salt, and maintaining plant growth.

The results above indicated that the drip-irrigation triggered by certain SMP thresholds were efficient for saline soil reclamation. But the leaching amounts, which are very important for salt leaching and watertable controlling in low-lying area, were not well analyzed in present studies. Wang et al. (2014) used the locate flux method to estimate the deep percolation at 120 cm depth in a field experiment that using the drip-irrigation under plastic film for the cotton cultivation. And they found the amounts of deep percolation decreased linearly from 18 to 3 mm when the controlled SMP thresholds reduced from − 5 to − 25 kPa within single growing season. Such small amounts of leaching water help with watertable controlling in the low-lying areas. But the leaching amounts and the amounts of groundwater recharge under drip-irrigation remain unclear for perennial plants cultivation in low-lying area with heavy salinity, especially for those in semi-arid or arid regions.

Modeling method is used to help with a comprehensive understanding of water and salt dynamics under drip-irrigation. The steady-state models were established several decades ago to set irrigation guidelines, and are still widely used to assess the suitability of water for irrigation. These guidelines were established to develop simple relationships between irrigation water salinity, rootzone salinity and LF (Letey et al., 2011). Usually, the average ECe within rootzone and EC of irrigation water were functions of the LF for steady-state models, which was widely used for irrigation scheduling, salinity controlling and yield estimation for its simplicity and convenience (Rhoades et al., 1982; SCS, 1992; Corwin et al., 2007; Letey et al., 2011). The transient-state HYDRUS model has also been widely used in field scale (Lila et al., 2013; Simunek et al., 2008; Skaggs et al., 2004). However, a better understanding on the root growth, root distribution, plant water uptake and soil texture is essential to predicting accuracy when modeling the salt dynamics using HYDRUS model (Roberts et al., 2009; Selim et al., 2013; Wallender et al., 2007). Moreover, the salt dynamics are significantly affected by factors such as the groundwater dynamics, plant leaf area index and irrigation regimes (Abliz et al., 2016; Lu et al., 2015; Scudiero et al., 2014). Monitoring these factors within a single growing season of the annual plant is accurate and feasible, but it is difficult and costly for perennial plant over years.

Thus, this study carried a 3-year field experiment, adopting the multi-stage drip-irrigation for vegetation construction in saline soil, to mine the dynamic characteristics of soil salinity over the long period using the semi-empirical and semi-theoretical approach derived from steady-state model. And this study mainly focused on: (1) analyzing the salt changes within growing season quantitatively; (2) estimating the amounts of leaching and groundwater recharge; and (3) revealing the desalinization mechanism under the improved drip-irrigation scheduling.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Qingtongxia Experimental Station, the same as Dong et al. (2020) from 2015 to 2017. The station (38°1′43″ - 38°1′48″N, 105°56′29″- 105°56′36″E) is in Wuzhong County, the Ningxia Hui Autonomous Region, China. This area has temperate continental semi-arid climate. And the annual average temperature is 9.3 ℃ with the lowest and highest of − 23.7 ℃ and 36.7 ℃, respectively. The annual rainfall and the potential evaporation (PE) are around 260 mm and 2000 mm, respectively. The perennial average groundwater depth in this area is 1.2 m with EC of 20 dS/m and pH of 8.5 before experiment. The physical and chemical properties of the tested soil are showed in Table 1. The 0–80 cm soil is sand and that in 80–120 cm is sandy loam. The average pHe and ECe in 0–120 cm are 7.64 and 10.4 dS/m, classified as heavily saline soil (Bao, 2000).

2.2. Experimental design

Experimental treatments were described in detail in the author's former study (Dong et al., 2020). Five soil matric potential (SMP) treatments, marked with S1-S5, were set up with SMP thresholds controlled at − 5, − 10, − 15, − 20, and − 25 kPa, respectively, exactly under drip emitters at both 0.2 m and 0.5 m. Each treatment consisted of 3 replications and there were 15 experimental plots in total, which were in a random arrangement. Two tensiometers were buried exactly under drip emitters at 0.2 and 0.5 m in the second repeating plot in every treatment, wrapped up by non-saline loamy soil paste (Fig. 1A), to make sure the probes were in firm contact with the soil. The irrigation of 5 treatments would be controlled by their matched SMP thresholds. Once SMP values of 0.2 or 0.5 m depths in a treatment reduced to SMP threshold, the treatment would be irrigated 10-mm water. The amount of 10 mm water for single irrigation was more than 6 mm that adopted in semi-humid areas by Chen et al. (2015) and Li et al. (2015a), because extra water was needed for leaching salt and meeting more ET in semi-arid area.

2.3. Plot layout and the improved irrigation scheduling

The saline soil was ridged by excavator at an interval of 4 m and the height of ridge was 0.8 m. Each plot had four 12-m long ridges and plants were planted on the top ridges. The 2-year old poplar trees (*Populus×canadensis Moench*) were planted in the transplanting hole at a space of 3 m. Five undershrub species were transplanted at a space of 1.5 m on two sides of one single ridge (Fig. 1A). The grass was sown in 5 rows on each ridge (Fig. 1A). All the plants were placed at a lateral separation of 0.1 m from drip tapes. The experimental area was surrounded by 3 drainage ditches with depth of 1.5 m and width of 2.0 m. And the planting details were described in the former study (Dong et al., 2020).

Each treatment had an independent irrigation controller to irrigate 3 repeating plots. There were 16 drip tapes on ridges and 4 drip tapes in furrows in each repeating plot with an area of 16 m × 12 m. Drip tapes, with emitter space of 0.3 m apart and discharge rate of 1.38 L/h at 10 m water head, were placed at an interval of 0.6 m on each top ridge (Fig. 1).

Table 1
Physical and chemical properties of experimental soil.

Soil layer (cm)	Soil mechanical composition (%)			Soil texture	Soil bulk density	EC_e/	pH_e	SAR/ $(mmol/L)^{0.5}$
	Clay	Silt	Sand		$(g\ cm^{-3})$	$(dS\ m^{-1})$		
0–10	0.84	4.70	94.47	Sand	1.36	10.11	7.55	20.27
10–20	0.27	3.96	95.77	Sand	1.48	7.91	7.48	14.73
20–30	1.01	7.29	91.70	Sand	1.41	7.79	7.51	14.58
30–40	0.67	4.50	94.83	Sand	1.57	6.20	7.47	10.31
40–60	0.12	3.33	96.56	Sand	1.57	8.06	7.54	13.50
60–80	0.58	4.27	95.16	Sand	1.59	10.09	7.63	21.88
80–100	2.06	34.61	63.33	Sandy loam	1.59	13.82	7.81	32.45
100–120	3.36	43.65	52.99	Sandy loam	1.56	15.67	8.02	39.25

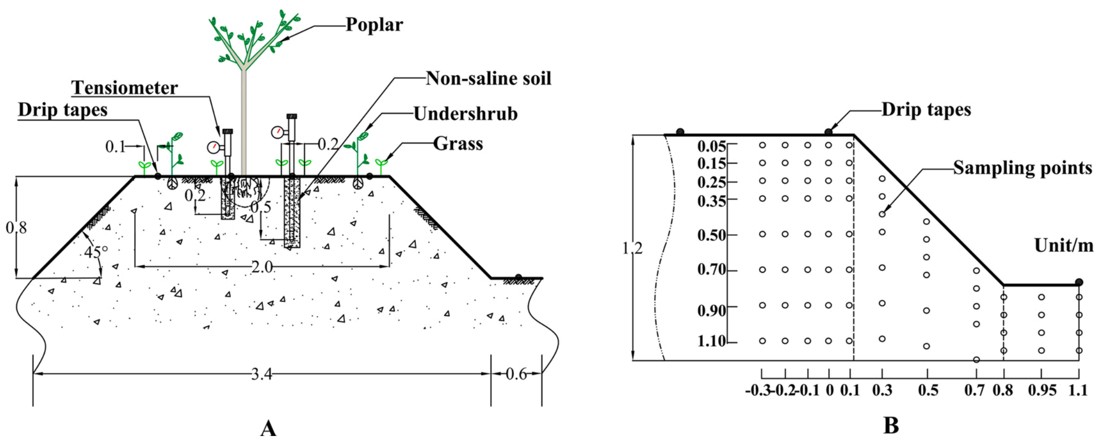

Fig. 1. Layouts of experimental arrangement from cross-sectional view (A) and soil sampling (B).

Irrigation water was drawn from the Yellow River, with annually average EC of 0.86 dS/m, pH of 7.95, and the irrigation water quality was introduced in a related study (Dong et al., 2020). The improved irrigation scheduling was divided into 3 stages and the details were described in the author's former study (Dong et al., 2020). The enhanced leaching stage (Stage I) started immediately after plants were transplanted (from 1 June 2015 to 6 June 2015), during which drip-irrigation was conducted continuously for 5 days in all treatments. Based on previous study (Chen et al., 2015; Li et al., 2016; Wan et al., 2012), the total irrigation water amount in Stage I should be no less than 40 mm. The conventional leaching stage (Stage II) started following Stage I. All treatments would receive 10-mm water if 2 out of 10 SMP values fell below − 5 kPa. Stage II lasted for at least 45 days (from 7 June 2015 to 22 July 2015) to leach salt and ensure that all transplanted plants being established well. The precise water and salt regulation stage (Stage III) was carried out as soon as Stage II was over (after 23 July 2015). When the SMP values of each treatment reduce to the matched SMP threshold, irrigation was conducted in that treatment.

In the first irrigation (early May, Spring irrigation) and last irrigation (early November, Winter irrigation) of one growing season, the applied water for all treatments was the same and no less than 40 mm.

2.4. Measurements

2.4.1. SMP

The SMP values monitored by tensiometers (WST-2B, Waterstar, Beijing, China) at both 0.2 and 0.5 m depths in all treatments were recorded twice a day at 8:00 and 15:00.

2.4.2. Groundwater dynamics

The depth and EC of groundwater were measured monthly through a PVC tube with holes drilled on the wall, which was buried in the middle of the experimental area.

2.4.3. Soil sampling and ECe

Soil samples were taken from each plot with an auger (4 cm diameter and 10 cm high) according to the sampling sketch in Fig. 1B. Soil samples were collected when Stage I and Stage II terminated, and then collected at an interval of 1–2 months in Stage III of the first 2 years and at the beginning and the end of the third growing season.

All soil samples were air dried and sieved through 2-mm sieve. Three replicate soil samples mixed to one sample to make extract of saturated soil paste by standard method (Robbins and Wiegand, 1990). Electrical conductivity of the saturated soil extracts (ECe) was determined by a conductivity meter (DDS-11A, Yulong, Shanghai, China).

The average ECe of the whole profile was calculated as weighted average value that taking the distance and area as weight factors (Dong et al., 2020).

2.5. Methods and models

2.5.1. Leaching fraction estimation

The leaching fraction (LF) is very important to salt leaching and controlling. According to the Section 15 Irrigation in National Engineering Handbook (SCS, 1992), the relationship between LF and the ratio of soil salinity within rootzones to salinity of irrigation water could be described by experience curves. The empirical curve under high-frequency irrigation condition, such as drip-irrigation, could be expressed as the following equation (Rhoades et al., 1982):

$$LF = 0.195 \cdot \left(\frac{EC_t}{EC_i}\right)^{-2.95} \tag{1}$$

Where LF is the leaching fraction; EC_t is the anticipated salt threshold within certain depth taking ECe as the standard; EC_i is the EC of irrigation water.

2.5.2. Groundwater recharge estimation

The equation for the change in salt storage, ΔS_S, is the following (ASCE, 2011):

$$\Delta S_s = D_rC_r + D_gC_g + D_iC_i + S_m + S_f - D_dC_d - S_p - S_c \tag{2}$$

where D = water depths; C = salt concentration; the subscripts r, i, g, and d designate rain, irrigation, upward flow from groundwater, and drainage, respectively; S_m = the salt dissolved from minerals in soil; S_f = the salt added to soil as a fertilizer or amendment; S_p = the salt precipitated; and S_c = the salt removed in the harvested crop.

In this study, the soil is sandy and the fertilizer for tree cultivation was negligible. Thus, we assumed that there were no salt dissolve or precipitation, no salt adding and removing in this study. The Eq. (2) could be simplified to Eq. (3):

$$\Delta S_s = D_rC_r + D_gC_g + D_iC_i - D_dC_d \tag{3}$$

The saturated soil pastes that determined the ECe of soil samples were made in an approximate ratio of soil to water by weight as 5:3 in this study. And the electrical conductivity (EC) of a solution is linearly correlated to its salt content when the EC is less than 20 dS/m (ASCE, 2011; White, 2006). The salt content of rainfall is supposed to be zero. Thus, the Eq. (3) can be replaced by Eq. (4):

$$0.6D_s\rho_s\overline{\Delta ECe} = D_g\rho_g\overline{EC}_g + D_i\rho_i\overline{EC}_i - D_d\rho_d\overline{EC}_d \tag{4}$$

where D_s = soil depth of the analyzing layer; ρ_s = soil bulk density; $\overline{\Delta ECe}$ = changes of the average ECe in the analyzing layer; $\overline{EC}$ = average EC.

Supposing that the ρ_g, ρ_i and ρ_d are equal to the density of pure water, the total salt in applied water, with leaching amount subtracted, is stored in the 0–40 cm soil layer, and the EC of leaching water was not less than that of the irrigation water. Then, the minimum recharge amount (MRA) from groundwater to 0–40 cm soil layer could be calculated by Eq. (5):

$$MRA = \frac{0.6D_s\rho_s\overline{\Delta ECe} - D_i\overline{EC}_i + D_d\overline{EC}_d}{\overline{EC}_g} \tag{5}$$

2.5.3. Desalination simulation

The Gompertz equation was used to describe the processes of the developing things related to agriculture and chemistry (Anguelov et al., 2017; Wang et al., 2015; Zhu et al., 2017). Thus, the Gompertz equation was adopted to simulate the desalinization processes of different treatment:

$$RDR = a\cdot\exp(-\exp(-(x - x0)/b)) \tag{6}$$

Where RDR is relative desalinization rate, calculated as the decreased values divided by the initial value; x is the total days of experiment; a, b, and x0 are parameters.

3. Results

3.1. SMP, rainfall and irrigation

Daily SMP changes of different treatments at 20-cm depth in the growing seasons from 2015 to 2017 are showed in Fig. 2. Since all treatments received the same irrigation water at irrigation Stage I and II in 2015, SMP values of all treatments were controlled between − 5 kPa and − 10 kPa and none obvious differences were found between treatments from 2015/6/15 to 2015/7/25. The SMP dynamics at Stage III in three seasons had remarkable differences between treatments. The SMP in different treatments basically fluctuated around their corresponding thresholds and the fluctuation became more sharply as SMP threshold becoming lower, which is in accordance with the previous studies (Chen et al., 2015; Jiao and Kang, 2007; Li et al., 2015a). Obviously, rainfalls increased SMP values in all treatments (black arrows), and thus a couple of days would be taken to again reach the SMP thresholds. For the most of time without rainfalls, SMP values of all

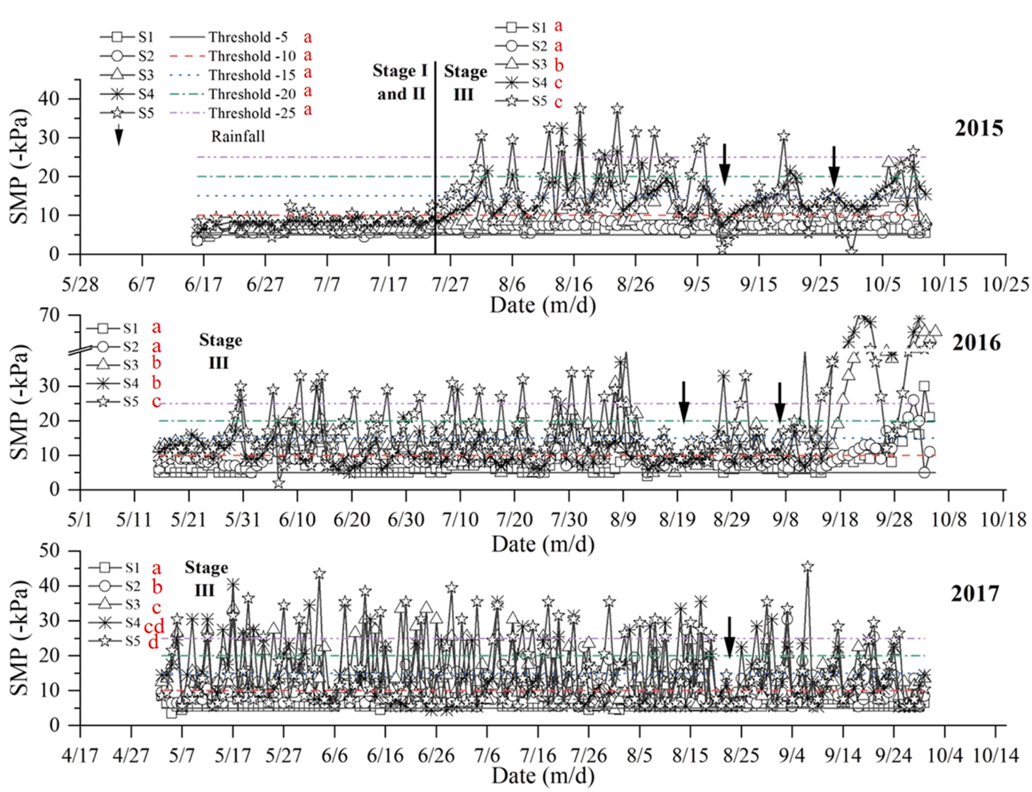

Fig. 2. Daily SMPs changes in different treatments at 20 cm depth directly under drip emitters during growing seasons of 2015, 2016 and 2017. (Note: different lowercases after treatment legend mean statistic difference at $P < 0.05$).

treatments were controlled around their thresholds very well and performed as they were anticipated.

The sum of applied water and rainfall (SAWR) in Table 2 showed that values of SAWR in all treatments were the same 88 mm in the Stage I and the same 386 mm in Stage II in 2015. Values of SAWR in S1 – S5 gradually decreased from 417 to 123 mm in Stage III of 2015. And values in S1 – S5 decreased from 732 to 257 mm in 2016 and from 971 to 426 mm in 2017. The SAWR decreased as SMP threshold decreased in all three growing seasons. And the SAWR in every treatment increased along with the increase of planting years and its ratio to that in S1 treatment also increased yearly, as a result of tree growths year by year. The prominent difference of winter irrigation between 2015 and 2016 could be attributed to the difference of soil moisture at the end of the two growing seasons.

3.2. Soil salinity and groundwater dynamics within growing seasons

Dynamics of ECe in 0–40 cm soil layer (ECe-40) were shown in Fig. 3. The salt was leached sharply in all treatments in Stage I and II, during which the average ECe-40 reduced from 8.00 to 0.66 dS/m within only 57 days. The 474 mm applied water in these two stages (Table 2) played an important role in this efficient leaching. When treatments conducted in Stage III in 2015–2017, the ECe-40 value in S1 treatment kept stable and those in other treatments showed confirm increases along with time within single growing season. The ECe-40 increments (Table 3) basically increased as SMP threshold decreased in 2015 and 2016. Although increases of ECe-40 were found in the third growing season (Stage III in 2017), the increments were only 0.17, 0.04, 0.19, 0.21 and 0.64 dS/m for S1-S5 treatments, which were less than the former two growing seasons. The SMP threshold that scheduled irrigation had prominent influence on salinity dynamics within growing season and the higher the SMP threshold was set, the less salt was built up. By the way, the sharp ECe-40 drops in all treatments between the end of one growing season and the beginning of the next growing season would be attributed to the winter irrigation.

The groundwater dynamics (Fig. 4) indicated that groundwater depth decreased from 1.6 m to 1.2 m after Stage I and II. The elevation of the groundwater was caused by the 474 mm water for salt leaching in Stage I and II (Table 2). When treatments conducted in Stage III in 2015, the groundwater depth decreased gradually and remained around the initial 1.6 m in 2016 and 2017 growing seasons. The EC of groundwater before experiment was 20 dS/m and that increased to 35.9 dS/m in Stage I and II, as a result of salt leaching. Then continuous decrease of groundwater salinity was found with the average EC values of 16.0, 15.4 and 10.7 dS/m in the Stage III in 2015, 2016 and 2017, respectively.

3.3. The leaching fraction (LF) and groundwater recharge within growing seasons

The LF that calculated by the Eq. (1) was shown in Table 4. The LF in Stage I and II in 2015 was 42.6% and its corresponding leaching amount was 202 mm. The LF showed differences among treatments during Stage III in 2015. LF values were 29.2%, 10.2%, 3.7%, 6.2% and 3.1% in S1-S5 treatments and their corresponding leaching amounts were 122, 31, 6, 9 and 4 mm in this stage. The situations of LF in both 2016 and 2017 were very similar to those in 2015. LF values and leaching amounts basically decreased as SMP threshold decreased in both Stage III in 2016 and 2017. The average LF values in Stage III among three growing seasons were 18.4%, 8.0%, 4.8%, 3.8% and 2.5%, with the correspondingly average leaching amounts of 114, 39, 19, 10 and 6 mm, in S1-S5 treatments.

The minimum recharge amounts (MRAs) from groundwater in Table 5, calculated by Eq. (5), indicated that the MRAs from groundwater to 0–40 cm soil layer in Stage I and II in 2015 were zero in all treatments. This might be attributed to the LF as high as 42.6% (Table 4), which caused a continuous and rapid decrease in soil salinity during this stage (Fig. 3). The MRAs were 0, 7.2, 28.2, 17.7 and 44.4 mm in treatments S1-S5, respectively, in Stage III in 2015, which were in accordance with the increments of the ECe during this stage (Table 3). During Stage III in 2016, the MRAs in S1-S3 were zero and those in S4 and S5 were 14.7 and 19.8 mm. But those were zero in all treatments during Stage III in 2017. This indicated that the MRAs reduced with the reclaiming years and keeping the SMP thresholds at − 5, − 15 and − 25 kPa in Stages III of the first 3 years, respectively, could ensure that little saline groundwater recharging to the 0–40 soil layer.

Table 2
The sum of applied water and rainfall of 5 treatments in growing seasons.

Growing seasons	Irrigation stages	The sum of irrigation and rainfall (mm)				
		S1	S2	S3	S4	S5
2015	Stage I	88	88	88	88	88
	Stage II	386	386	386	386	386
	Stage III	417	301	166	139	123
	Winter Irrigation	30	30	30	30	30
2016	Spring Irrigation	40	40	40	40	40
	Stage III	732	509	371	320	257
	Winter Irrigation	70	70	70	70	70
2017	Spring Irrigation	50	50	50	50	50
	Stage III	971	746	579	491	426

3.4. Inter-annual salt dynamics

The RDR dynamics in different soil layers along time were showed in Fig. 5. During irrigation Stage I and II, the salt was leached quickly with the RDR values of 90%, 80% and 70% for 0–40, 40–80 and 80–120 cm, respectively, by the end of Stage II. The soil desalinization process became slow and sinusoidal shaking in Stage III.

The salt dynamics in 0–40 cm soil layer were strongly correlated to SMP thresholds (Figs. 5A and 6A). As SMP threshold decreased, the RDR decreased and the average ECe in Stage III in this soil layer increased linearly. RDR values of all treatments fluctuated between years and the lower the SMP thresholds, the greater the amplitude (Fig. 5A).

The temporal dynamic of RDR in 40–80 cm soil layer (Fig. 5B) was like those in 0–40 cm soil layer. A linear relationship between ECe and SMP threshold was also found in this soil layer (Fig. 6B). The salt dynamics in this soil layer in treatments S3 and S4 exhibited a salt stable state, while those in the other 3 treatments remained variable states. The results suggested that keeping the SMP thresholds at a range of − 20 to − 15 kPa could formed a salt stable layer at 40–80 cm depths.

Differences of temporal dynamics of salt in 80–120 cm soil layer (Fig. 5C) were found when compared with the former 2 soil layers. The RDR at the beginning of growing seasons in this layer was less than that at the end of growing seasons, revealing that the soil salt increased after non-growing seasons in this soil layer. A linear regression relationship between average ECe and SMP was also valid though the ECe in S3 was abnormally high (Fig. 6C). The RDRs in treatment S1 and S2 kept stable along time in this layer, suggesting a SMP range of − 10 to − 5 kPa could form a salt stable layer at 80–120 cm depths.

RDR values in ridge slope kept stable in all treatments in Stage III and the temporal dynamics of salt could be simulated by Gompertz equation (Fig. 5D). However, the ECe decreased at first and then increased as SMP decreased (Fig. 6D), which was different from that in 0–120 cm soil layers above.

RDR values in the whole soil profile of different treatments along time were simulated by Eq. (6). The salts in all treatments were leached quickly in Stage I and Stage II and gradually became stable along time in irrigation Stage III, except S3 treatment (Fig. 7). The simulation results (Table 6) indicated that the stable RDR decreased as SMP thresholds decreased, with values of 81.84%, 75.06%, 67.77% and 64.69% for S1, S2, S4 and S5. The stable ECe values for S1, S2, S4 and S5 were 1.89, 2.60, 3.36 and 3.82 dS/m, respectively, classified as non-saline soil based on classification criteria (Richards, 1954). To be noted, the RDR in

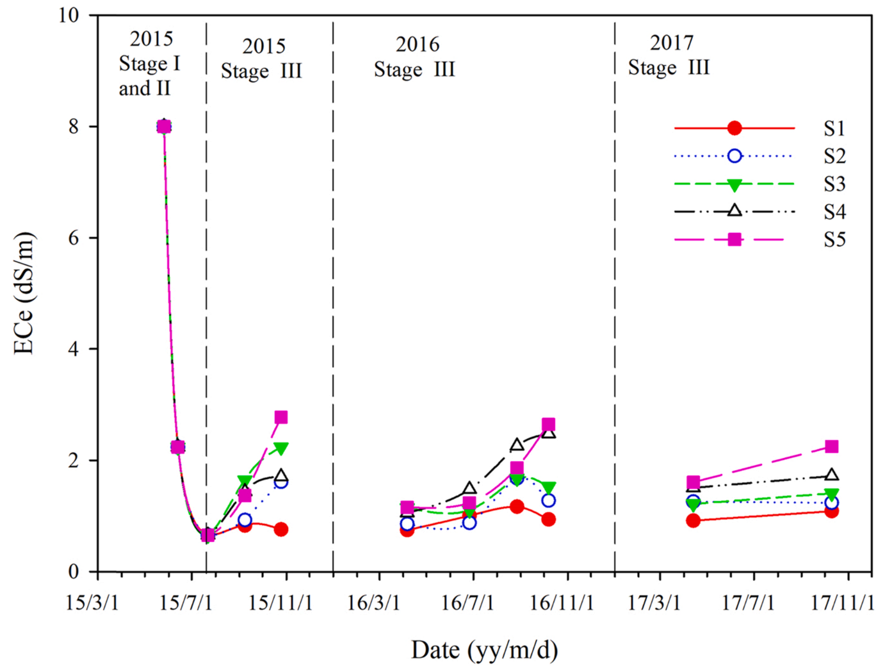

Fig. 3. The dynamic of ECe in 0–40 cm soil layer in three growing seasons.

Table 3
The increments of ECe in 0–40 cm soil layer in all treatments in Stage III in three growing seasons.

Periods	ECe increments (dS/m)				
	S1	S2	S3	S4	S5
Stage III in 2015	0.10	0.96	1.58	1.05	2.12
Stage III in 2016	0.19	0.42	0.38	1.42	1.49
Stage III in 2017	0.17	0.04	0.19	0.21	0.64

treatment S3 didn't seem to be stable along time and had a tendency of salt accumulation in the whole soil profile along time, which was in accordance with the salt dynamics in 80–120 cm (Fig. 5C and Fig. 6C) and ridge slope (Fig. 5D and Fig. 6D) soil layers.

4. Discussion

4.1. The efficiency of the improved drip-irrigation scheduling for salt reclamation

The leaching requirement (LR) is of vital importance to the soil salinity control in the irrigated areas in arid or semi-arid region. The LR was defined as the fraction of infiltrated water that must pass through the rootzone to keep average rootzone soil salinity from exceeding a level that would significantly reduce crop yield, assuming steady-state conditions with associated good management and uniformity of leaching (USDA, 1954). The LR is calculated by the product of the applied water amount and the leaching fraction (LF). The LF is calculated by the ratio of the EC of the irrigation water to that of the drainage water or other empirical equations (ASCE, 2011). When developing an irrigation

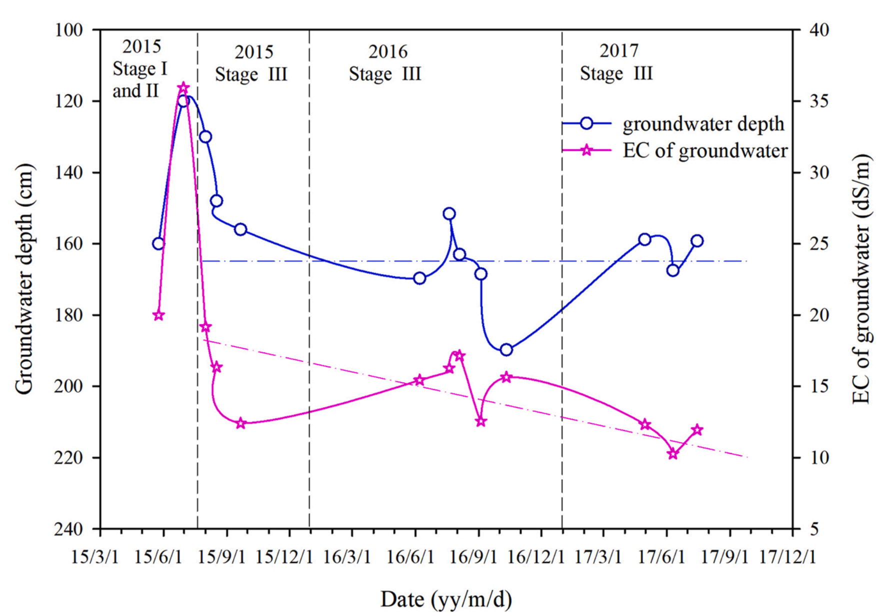

Fig. 4. Dynamics of depth and electrical conductivity (EC) of groundwater in three growing seasons.

Table 4
The leaching fractions and amounts in different treatments during different irrigation stages. (Note: the data was calculated taking 0–40 cm soil layer as analyzing zone.)

Periods	Leaching fractions (%)					Leaching amounts (mm)				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Stage I and II in 2015	42.6	42.6	42.6	42.6	42.6	202	202	202	202	202
Stage III in 2015	29.2	10.2	3.7	6.2	3.1	122	31	6	9	4
Stage III in 2016	13.8	7.8	5.0	2.1	2.5	101	40	18	7	6
Stage III in 2017	12.3	6.0	5.6	3.0	1.8	120	45	32	15	8

Table 5
The minimum recharge amounts from groundwater in different treatments during different irrigation stages. (Note: the data was calculated taking 0–40 cm soil layer as analyzing zone).

Periods	The minimum recharge amounts from groundwater (mm)				
	S1 (- 5 kPa)	S2 (- 10 kPa)	S3 (- 15 kPa)	S4 (- 20 kPa)	S5 (- 25 kPa)
Stage I and II in 2015	0.0	0.0	0.0	0.0	0.0
Stage III in 2015	0.0	7.2	28.2	17.7	44.4
Stage III in 2016	0.0	0.0	0.0	14.7	19.8
Stage III in 2017	0.0	0.0	0.0	0.0	0.0

scheduling for salt control, the accurate ET must be known (ASCE, 2011; White, 2006). Usually, the ET is estimated by the FAO 56 Penman-Monteith method and its accuracy is influenced by the diversities of the climatic zones and ground conditions (Dhungel et al., 2014; Tadesse et al., 2018). Thus, the LF calculation based on an estimated ET would cause prominent difference between the actual LF and the designed LF (ASCE, 2011). The drip-irrigation for the salt reclamation in this study is scheduled by the SMP threshold and the ET is no need to be estimated. Though the LF was not intentionally designed for the drip-irrigation scheduled by the SMP threshold in this study, the LF did exist and reduced as the SMP threshold decreased. The multi-stage drip-irrigation scheduling showed high efficiency in the salt leaching in Stages I and II (with the LF as high as 42.6%) and salt control in stage III. Thus, compared with the traditional irrigation scheduling for salt control that calculates the LF and estimate the actual ET, this improved drip-irrigation scheduling has advantages of simplicity, convenience and accuracy and a certain leaching ratio is maintained if a proper SMP threshold is determined in different irrigation stages.

The multi-stage drip-irrigation scheduling for salt reclamation has been widely used to saline-soil reclamation among different climate regions. In a semi-arid coastal region, Li et al. (2015b) found that the irrigation scheduled by the SMP thresholds at − 5 and − 15 kPa in the first 2 years respectively, could significantly decrease soil salinity and remain the 2-year survival rate higher than 80%, when using the irrigation water with EC of 3.1 dS/m. This prominent reclaiming effect might be attributed to the agronomy practice that setting a gravel-sand layer at the upper boundary of the groundwater to reduce capillary action and the rich rainfall that higher than 500 mm yearly. In the

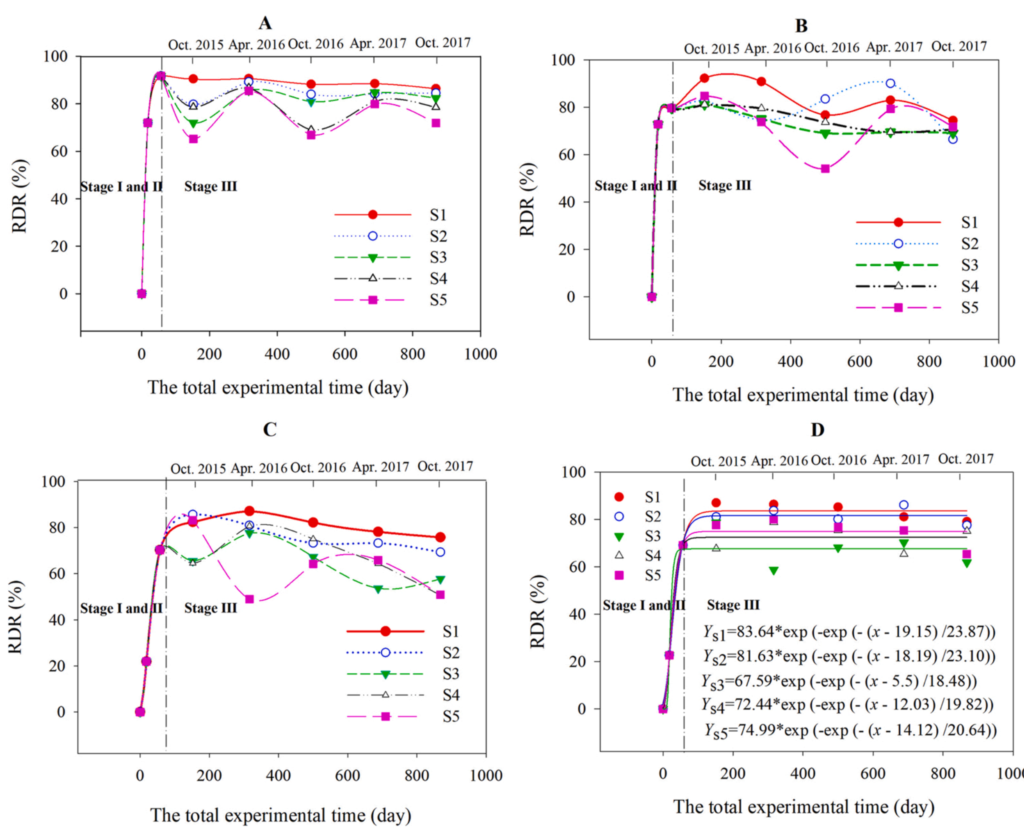

Fig. 5. Salt dynamics in different soil layers of different treatments, where A 0–40 cm soil layer, B 40–80 cm soil layer, C 80–120 cm soil layer and D soil layer in ridge slope. (Note: RDR is the abbreviation of relative desalinization rate).

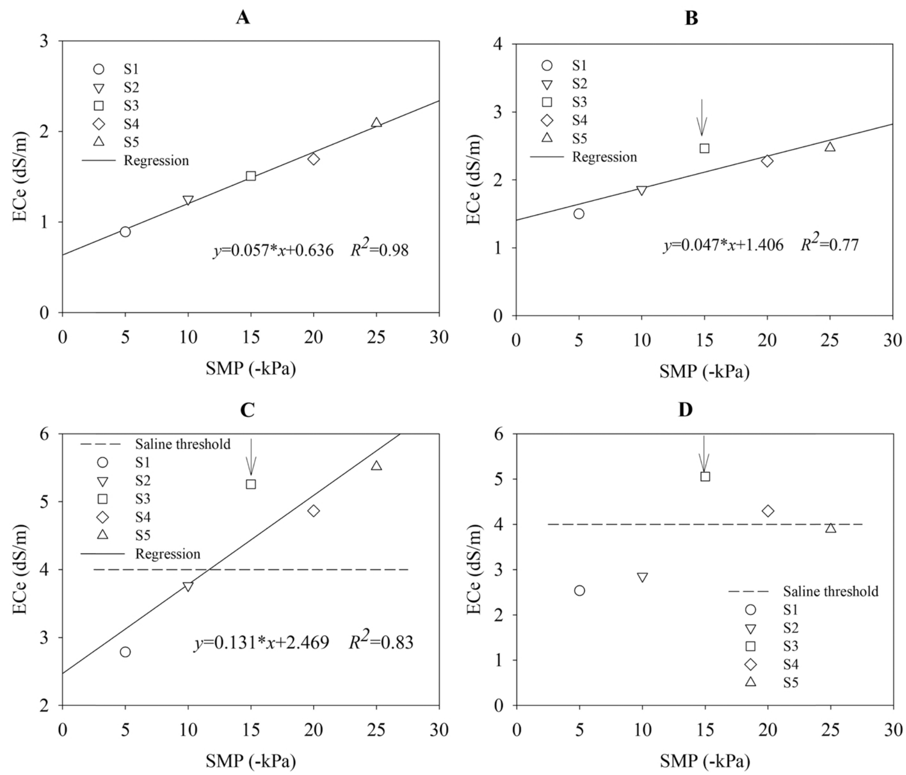

Fig. 6. Average ECe values in Stage III for each treatment and their relationships with SMP, where A 0–40 cm soil layer, B 40–80 cm soil layer, C 80–120 cm soil layer and D soil layer in ridge slope. (Note: Saline threshold is 4 dS/m, based on ECe.)

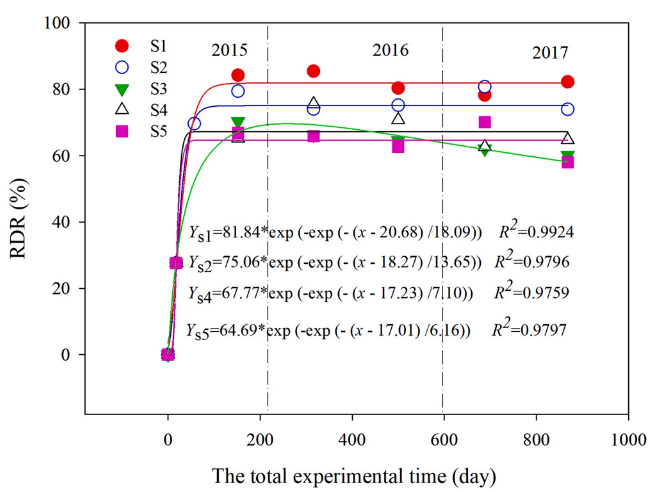

Fig. 7. Simulations of the relative desalinization rate (RDR) in the whole 0–120 cm soil layer along time for different treatments.

first-year experiment of Li et al. (2015b), the rainfall was as much as 883 mm, because of which the irrigation frequencies were decreased and the total irrigation water amount was only 210 mm though the SMP threshold was set at − 5 kPa (Table 7). In the second year, the irrigation water amount was 45 mm more than the first year but the LF decreased from 18.26% to 3.12%, when the SMP threshold decreased from − 5 to − 15 kPa. The rainfall in the second year was 400 mm less than the first year, which might be responsible for the LF difference between these 2 years. The study of Sun et al. (2013) seemed supporting the positive effect of isolation layer on salt leaching (Table 7). They found that the ECe within 0–40 cm was 1.5 dS/m and the LF was 39.16% when isolation layer was set, while those were 4.4 dS/m and 1.64% when there was none isolation layer, based on a 3-year experiment with a similar condition of Li et al. (2015b). The study in this paper was in a semi-arid region with annual rainfall around 110 mm and the soil was sandy, which were quite different from the studies of Li et al. (2015b) and Sun et al. (2013). The high ridge played a similar role of isolation layer to reduced capillary action and the increased irrigation amount could make up for the difference in rainfall between arid and humid regions. Thus, LF around 13% and 3% could be maintained when SMP threshold was set at − 5 and − 20 kPa, respectively, in this study (Table 7). Soil texture did not seem to have influences on LF when the appropriate agronomy practices were applied, however, the average ECe

Table 6
Parameters of RDR simulation curves by Gompertz equation.

Treatments	Y = a*exp (-exp(-(-x-x0)/b))			R^2	sig	Stable desalination rate (%)	Inflection point (d)	Stable ECe (dS/m)
	a	b	X_0					
S1	81.84	18.09	20.68	0.992	***	81.84	21	1.89
S2	75.06	13.65	18.27	0.980	***	75.06	18	2.60
S3	—	—	—	—	—	—	—	—
S4	67.77	7.10	17.23	0.976	***	67.77	17	3.36
S5	64.69	6.16	17.01	0.980	***	64.69	17	3.82

Table 7
Summary of the leaching fraction (LF) using the scheduled drip irrigation for soil salt reclamation in different regions. (The data of region 1 was from Li et al., 2015b, the data of region 2 was from Sun et al., 2013, and the data of region 3 was from this study. *The LF in the table was calculated by Eq. (1).)

Region	Reclaiming years	Agronomy practices	Soil texture	SMP threshold (kPa)	Rainfall (mm)	Irrigation amount (mm)	0–40 cm ECe (dS/m)	Calculated LF (%)*
Semi-humid[1]	1	Isolation layer	Silt loam	-5	883	210	3.17	18.26%
	2	Isolation layer	Silt loam	-15	489	255	5.77	3.12%
Semi-humid[2]	3	Isolation layer	Silt loam	-5	616	270	1.5	39.16%
	3	None	Silt loam	-5	616	250	4.4	1.64%
Semi-arid[3]	2	High ridge	Sand	-5	115	776	0.97	13.67%
	2	High ridge	Sand	-20	115	364	1.82	2.14%
Semi-arid[3]	3	High ridge	Sand	-5	100	921	1.01	12.14%
	3	High ridge	Sand	-20	100	441	1.62	3.01%

in silt loam soil was basically larger than that in sandy soil (Table 7). The reason might be attributed to the differences of soil adsorption capacity for ions. Furthermore, regardless of the differences of climate conditions and soil texture, the total infiltrating water (irrigation water + rainfall) was between 900 mm and 1100 mm when the SMP threshold was set at − 5 kPa, and the LF greater than 2% could be maintained when the SMP threshold was set at − 20 kPa. This indicated that the drip-irrigation scheduled by SMP threshold was efficient in saline-soil reclamation, and it was little affected by the diversities of climate types and soil textures under the conditions that the key SMP thresholds were determined and the proper agronomy practices, such as isolation layer or ridging, were adopted.

4.2. The fate of salt under the improved drip-irrigation in the long run

Generally, field capacity (FC) corresponds to SMP between − 5 and − 10 kPa. For well-structured soils, the SMP at FC is set at − 5 kPa, whereas for others, it is set at − 10 kPa (Cavazza et al., 1973; White, 2006). In this study, SMPs in treatment S1 (−5 kPa) and S2 (−10 kPa) were basic higher than the SMP at FC (−10 kPa) for most of the time. Thus, the soil water in these two treatments would keep a trend of downward movement and a salt equilibrium state could be formed in 80–120 cm soil layer (Fig. 5C). For treatments S3 (−15 kPa) and S4 (−20 kPa), the SMPs would be less than the SMP at FC (−10 kPa) until irrigation was conducted. The salt equilibrium state was formed in 40–80 cm soil layer (Fig. 5B) in these two treatments. As for treatment S5 (−25 kPa), there was no salt equilibrium state formed in 0–120 cm soil layer. This indicated that when the SMP threshold was set larger than − 20 kPa, salt could be controlled at an equilibrium state in 40–120 cm depth, and the threshold larger, the depth deeper. This raised a question that what was the fate of the original soil salt. The groundwater dynamics (Fig. 4) suggested that the groundwater depth decreased and the EC increased drastically during the irrigation Stage I and II, owing to the LF of 42.6% (Table 4). Then during the Stage III, the groundwater depth gradually increased and kept stable around 165 cm. And the EC of groundwater kept a firmly decreasing trend, with a decrease from the 35 dS/m at the beginning to the 12 dS/m at the end. The groundwater dynamics explained that the soil salt was leached quickly to the groundwater during the leaching Stage I and II, and then the salt was gradually transported to the out zone of the experimental area through lateral groundwater discharge. In a comprehensive consideration of the soil salt dynamics and groundwater dynamics, the key SMP thresholds of − 5 kPa in Stage II and − 20 kPa in Stage III were essential to ensure salt leaching and external transfer, which was in accordance with the result of Dong et al. (2020).

To be noted, the inter-annual salt dynamics suggested that the average salt within 0–120 cm depth in S3 (−15 kPa) treatment tended to increase along time (Fig. 7), which was different from the rest treatments with equilibrium state. The salt increments in 80–120 cm soil layer (Fig. 5C) and soil layer in slope (Fig. 5D) mainly accounted for this phenomenon. The similar result of salt distribution in S3 was also reported by the author's former study in another experiment (Dong et al., 2021). They believed that the tree in the medium moisture conditions (e.g., S3 treatment), had deeper roots, greater coverage, and thus more water absorption by roots in deep soil than those in low moisture conditions (e.g., S4 and S5). Thus, the salt in 80–120 cm soil layer and ridge slope was more easily affected by capillary action in S3 than S4 and S5 once the water was absorbed by deep root. Under this circumstance, intentionally setting a relatively low SMP threshold in irrigation Stage III following the salt leaching Stage I and II, would be important to avoid salt building up again in deep soil layer in these low-lying areas with saline groundwater.

Using tensiometer scheduling drip-irrigation induced high irrigation frequency, which raised a very important question that how much applying water was needed to maintain the prosperity of plantation forests. Based on the first 3 year's data, if the SMP threshold was set at − 5 kPa for Stage II and − 20 kPa for Stage III, the applying water amounts were correspondingly 921, 430, and 541 mm for the first 3 years, which almost met the ET (525 mm) of healthy development of a sparse woodland in an arid region (Yang and Yang, 1988). Gou et al. (2017) conducted a willow forest establishing experiment in a same area as this study, finding that yearly applying 1800 mm water combined with ditches arranged at 9 m intervals in field was efficient to leach salt and ensure the establishment of the willow forest. The yearly 1800 mm water would raise the water table in the long run on the one hand, and increase water consumption pressure to the water shortage area on the other hand. As compared, the yearly applied water under multi-stage drip-irrigation in this study was less than one third of that of flood irrigation except in the first year, which saved more than 1200 mm available water yearly when compared with flood irrigation.

5. Conclusion

The improved drip-irrigation scheduling, consisted of the enhanced leaching (Stage I), the conventional leaching (Stage II) and the precise water and salt regulating (Stage III), was proved to be efficient in salt leaching and controlling. During the irrigation Stage I and II, soil salt was rapidly leached to groundwater owing to the LF as high as 42.6% and the MRA in all treatments were zero. When the irrigation Stage III began, the ECe-40 basically increased as the SMP thresholds decreased from − 5 kPa to − 25 kPa, which was caused by the correspondingly decreasing LF and increasing MRA.

The inter-annual salt dynamics indicated that the average ECe values in different soil layers were negatively linear correlated to the SMP thresholds. A salt equilibrium state was formed in the 80–120 cm soil layer when the SMP threshold was set larger than − 10 kPa, and a similar state was formed in the 40–80 cm soil layer when the SMP threshold was set between − 20 to − 10 kPa. The MRAs in all treatments and EC of groundwater decreased with the reclaiming years, indicating the whole experimental area was in a desalinization process as the multi-stage irrigation scheduling continued.

This improved drip-irrigation scheduling showed that the LF and MRA were controlled by the SMP thresholds, and thus account for the excellent performance in short-time salt leaching and long-run salt controlling, regardless of the differences of climate conditions and soil texture in different areas. Setting SMP threshold of − 5 kPa in Stage II to rapidly leach all soil salt into groundwater and − 20 kPa in Stage III to gradually drainage the salt and keep salt balance was recommended for ecological restoration in areas similar to that in this study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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