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RESEARCH ARTICLE

Effect of different water application intensity and irrigation amount treatments of microirrigation on soil-leaching coastal saline soils of North China

CHU Lin-lin[1, 2], **KANG Yao-hu**[2], **WAN Shu-qin**[2]

[1] *Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education/ College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P.R.China*

[2] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, P.R.China*

Abstract

In coastal regions, Bohai Gulf is one of the most affected areas by salinization. To study the effects of mocrosprinkler irrigation on the characteristics of highly saline sandy loam soil (ECe (saturated paste extract)=22.3 dS m^{-1}; SAR (sodium adsorption ratio)=49.0) of North China, a laboratory experiment was conducted. Five water application intensity (WAI) treatments (1.7, 3.1, 5.3, 8.8, and 10.1 mm h^{-1}), five irrigation amount (IA) treatments (148, 168, 184, 201, and 223 mm) and three time periods of water redistribution (0, 24 and 48 h) were employed in the study. A compounding microsprinkler system was used for the WAI treatments, and a single microsprinkler was used for the IA treatments. The results indicated that, as soil depth increased, soil water content (θ) increased and then slightly decreased; with WAI and IA consistently increasing, the relatively moist region expanded and the average θ increased. Meanwhile, soil ECe increased as soil depth increased, and the zone with low soil salinity expanded as WAI and IA increased. Although the reduction of the average SAR was smaller than that of the average electrical conductivity of the ECe, these variables decreased in similar fashion as WAI and IA increased under microsprinkler irrigation. The average pH decreased as soil depth increased. Longer time periods of water redistribution led to lower salinity and slight expansion of the SAR zone. Considering the effects of leached salts in coastal saline soils, greater WAI and IA values are more advantageous under unsaturated flow conditions, as they cause better water movement in the soil. After leaching due to microsprinkler irrigation, highly saline soil gradually changes to moderately saline soil. The results provide theoretical and technological guidance for the salt leaching and landscaping of highly saline coastal environments.

Keywords: coastal saline soil, microsprinkler irrigation, SAR, reclamation

1. Introduction

Bohai Gulf, including 3 provinces and 2 cities, *viz*., Hebei, Liaoning, Shangdong, Tianjin, and Beijing, is the key regional economic development belts in China (Wang *et al*. 2012). However, approximately 680 000 ha of salinity-affected land in this region is faced with land salinity threats (Liu and

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CHU Lin-lin, E-mail: LLchu5589@163.com;
Correspondence KANG Yao-hu, Tel/Fax: +86-10-64856516, E-mail: Kangyh@igsnrr.ac.cn

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Tian 2003). The salinity of coastal soils is high, with mean saturated paste extract (ECe) values of 16.7–66.7 dS m^{-1}, and possess the same ion composition as sea water (Wang *et al*. 1993; Khan *et al*. 1996). Moreover, the groundwater table, with a salinity of 5–20 g L^{-1}, is shallow (1.5–2 m) and deeper during winter than in summer (Shi *et al*. 2005; Chai *et al*. 2008), which makes the soils unsuitable for landscape plants that are not highly tolerant to salt (Sun *et al*. 2012). To meet the needs of rapid industrialization and urbanization, methods must be determined for the reclamation of coastal saline soils and for landscaping with lawns, shrubs and trees that are at least moderately tolerant to salinity (Grieve *et al*. 2012) along the roads and in the parks of the coastal areas of China.

Microsprinkler irrigation has gained attention over recent years because of its potential to increase yields and decrease water use, fertilizer and labor requirements (Song and Wang 2002; Reich *et al*. 2009). The method applies water directly to the soil surface area, allowing water to dissipate under low pressure in a wetted profile that uniformly meets water demand, and its drops produce little or no rainsplash, disturbing the natural structure of the soil to a much lesser degree than sprinkler irrigation (Hancock *et al*. 2003; Marco *et al*. 2003; Reich *et al*. 2009). It protects crops from adverse climatic conditions, which promotes better growth and yield (Spieler 1994). Compared to drip/furrow irrigation, microsprinkler irrigation is more appropriate for maximizing the profit per unit cropped area using the limited available water in a canal-irrigated semiarid environment (Satyendra *et al*. 2009). Some researchers have determined the feasibility of microsprinkler irrigation and the principles for selecting its technical parameters. Recently, many studies have been done to evaluate the use of different levels of water application intensity and irrigation amount of microsprinkler irrigation in coastal region with very strongly saline silt soil (Chu *et al*. 2014, 2015). They have found that after microsprinkler irrigation this kind soil gradually changed to a moderately saline soil. These studies developed appropriate treatments, but appropriate irrigation parameter varies according to different soils and regions, and so further studies are required to determine the effects of the method on soil water content (θ) and salinity in coastal saline soils.

To understand the effects of microsprinkler irrigation on coastal saline soils in further detail, laboratory experiments were conducted. The present study examined the influence of microsprinkler irrigation on the average θ, ECe, sodium adsorption ratio (SAR), and pH in coastal saline soils under different water application intensity (WAI) and irrigation amount (IA) treatments.

2. Materials and methods

2.1. Soil

The experiment was conducted at the Caofeidian Experimental Station for the afforestation and beautification of sandy, highly saline coastal zones. The station (latitude: 39°03´N; longitude: 118°47´E) is located in the Tangshan Industrial Development Zone, to the east of Hebei Province, west of the Bohai Gulf. The study area possesses a semihumid marine climate, with a mean annual temperature of 11.4°C and mean annual precipitation of 554.9 mm, 74% of which is concentrated from June to September. Due to the deposition of blown sand, the soil has low field capacity and high extract salinity. Seawater does not drain below the 50–60 cm soil layer. Additionally, the climate and special geographical conditions of this region make it susceptible to salt accumulation on the soil surface. For these reasons, the saline soils of the area are difficult to reclaim, and except for halophytes with high salt resistance, plants cannot grow on them.

Soil was sampled from the subsurface layer of the experimental site. The soil was a loamy sand, with 0.02% of particles less than 0.002 mm, 9.40% of particles between 0.002 and 0.02 mm, and 90.59% of particles larger than 0.02 mm. At 0–20 cm, the average bulk density of the experimental soil was 1.5 g cm^{-3}, the mass water content of field capacity was 20%, and its ECe, SAR and pH were 22.3 dS m^{-1}, 49.0 $(mmol\ L^{-1})^{0.5}$ and 7.8, respectively.

2.2. Experimental design

The laboratory experiments were conducted in organic glass pipe soil columns (Fig. 1-A) of 110 mm in diameter and 600 mm in height. Many holes (Fig. 1-B) spaced at 2 mm were drilled in the bottom of each soil column to drain off the deep percolation water. Each air-dried soil sample was filled into the soil column with an average soil bulk density of 1.5 g cm^{-3}, the average soil bulk density of the field experiment site. The soil column was filled with 12 layers of 5 cm each. After the addition of each layer, the soil column was tapped 30 times at random with a flat wooden rod. The experimental soil was uniform, with no obvious layered or secondary pores such as wormholes, root holes or dry cracks, and water movement was considered to be one-dimensional and vertical over the course of the experiment. Because the experiments were conducted indoors, air flow and temperature were not considered to effect evaporation.

The study included two parts: (1) the experiments for the water application intensity (WAI) of microsprinkler irrigation; (2) the experiments for the irrigation amount (IA) of microsprinkler irrigation (Fig. 1-D).

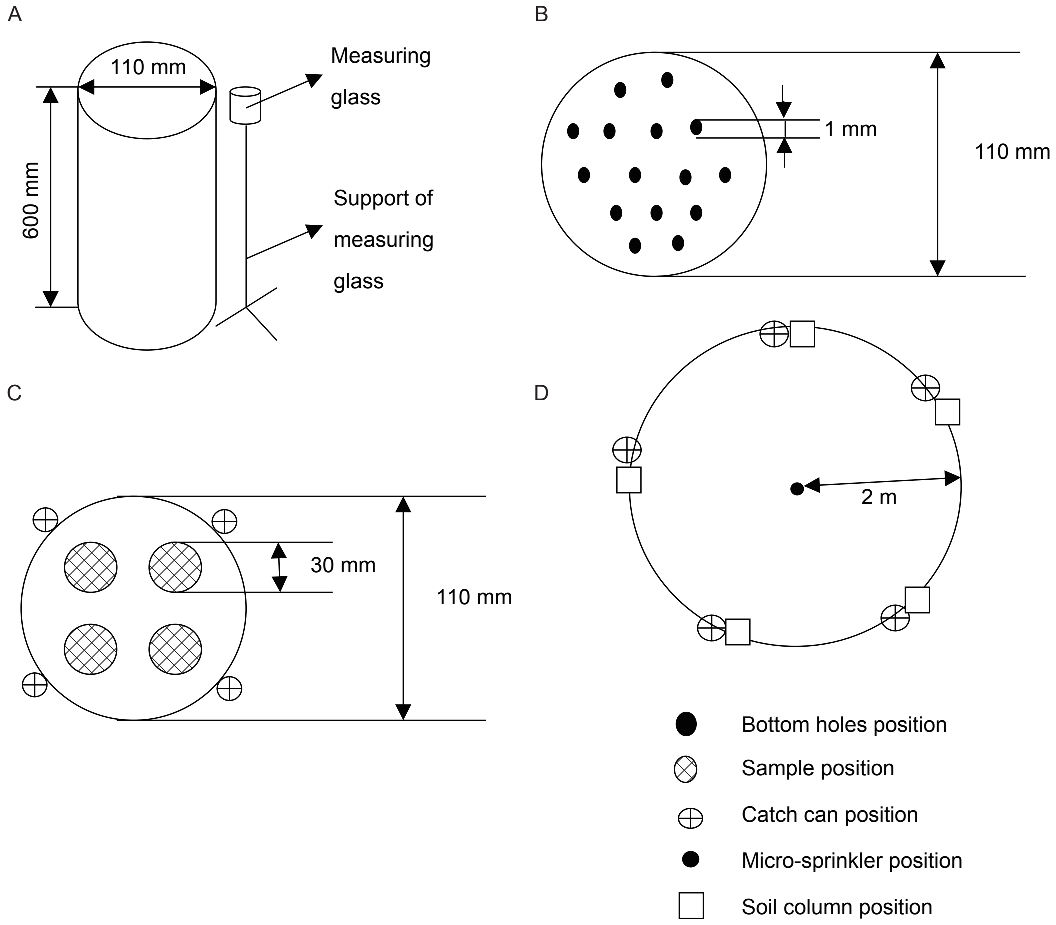

Fig. 1 Sketch maps of soil column and measuring glass (A), the bottom holes position of soil column (B), four samples position of soil column and their corresponding measuring glasses position (C), and schematic maps of laboratory experiments of different IA treatments (D).

Part 1: To obtain different WAI values, different numbers of single-nozzle microsprinklers were deployed in a circular pattern, with a spacing of 2 m between the microsprinklers and soil column (Fig. 2). When the IA reached the desired value, the soil column was covered immediately with plastic film, thereby ensuring that the five WAI treatments used the same amount of irrigation water.

Part 2: A microsprinkler with a single nozzle and wetting radius of 2.5 m was installed. Five water amounts were applied as experimental treatments (Fig. 1-D). All experimental points were selected in a concentric circle with a radius of 2 m. The microsprinkler was deployed at the center of the concentric circle. If any observation point received the desired water amount, this point was covered immediately with plastic film. After each treatment, the measuring glass was put on the position of the soil column to measure the irrigation amount. If the data of irrigation amount was within the error range, the next treatment would be started. On the contrary, the position of the soil column would be reselected until the data within the error range.

The small swivel microsprinkler, manufactured in plastic (Beijing Lüyuan Co.), was 65 cm in height. The nozzle operating pressure was kept at a constant 0.2 MPa using a hydraulic pressure control valve, and irrigation employed fresh water with an ECe of 0.4 dS m^{-1}, pH of 8.6 and SAR of 7.6 (mmol L^{-1})$^{0.5}$. All treatments were repeated three times.

2.3. Observations

Water application intensity (WAI) To evaluate the WAI value at a given point of the soil column, a catch can was installed between the microsprinklers and soil column (Fig. 1-D). After each irrigation event, the WAI value in each catch can was calculated according to eq. (1):

$$WAI=\frac{m_2-m_1}{\rho_w\times\pi\times r^2\times t}\times 10 \tag{1}$$

Where, WAI is water application intensity (mm h^{-1}), m_1 and m_2 are catch can qualities before and after irrigation, respectively (g), ρ_w is water density (g cm^{-3}), r is the inlet radius of the catch can (cm), and t is the duration of microsprinkler irrigation (h).

Five WAI treatments, 1.7, 3.1, 5.3, 8.7, and 10.1 mm h^{-1}, were employed in the experiment.

Irrigation amount (IA) The method for evaluating the IA value at a given point of the soil column is similar to that for evaluating WAI. The IA value was calculated by the following equation:

$$IA=\frac{m_2-m_1}{\rho_w\times\pi\times r^2}\times 10 \tag{2}$$

Where, IA is irrigation amount (mm).

Five IA treatments, 148, 168, 184, 201, and 223 mm, were employed in the experiment.

Soil water content and salinity Soil samples for each treatment were obtained from each soil column using an auger (3.0 cm in diameter and 100 cm in height) at 0, 24 and 48 h after soil water redistribution. The sample depths were 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, 35–40, 40–45, 45–50, 50–55, and 55–60 cm. After each sample was obtained, a plastic cloth was placed into the hole to avoid influencing other samplings.

θ was obtained from moist samples by the oven-drying method. The remaining soil samples were air-dried and sieved through a 2-mm sieve. Three replicate soil samples were mixed into one sample, and a saturated soil paste was then prepared by centrifugation (4 000 r min^{-1}, 20 min) for chemical analysis. Soil ECe, soluble cations (Na^+, Ca^{2+} and Mg^{2+}) and pH were determined in extracts of the saturated soil using a conductivity meter (DDS-11, REX, Shanghai), inductively coupled plasma optical emission spectrometry (Optima 5300DV, PerkinElmer, American) and a pH meter (PHS-3C, REX, Shanghai), respectively. The sodium adsorption ratio (SAR) of the saturated paste extract was calculated as follows:

$$\text{SAR}=\frac{(\text{Na}^+)}{[(\text{Ca}^{2+}+\text{Mg}^{2+})/2]^{0.5}} \tag{3}$$

Where, the concentration of each cation is in mmol L^{-1}.

The rate of desalinization was calculated by:

$$\text{ECe(R)(\%)}=\frac{\text{ECe(initial)}-\text{ECe(end)}}{\text{ECe(end)}}\times 100 \tag{4}$$

Where, ECe(R) refers to the rate of desalinzation, ECe(initial) and ECe(end) refer to the weighted mean value of the soil profile on the initial stage and the end of experiment during salt leaching.

3. Results and discussion

3.1. Irrigation

The WAI and IA experiments were initiated on September 17 and October 20, 2012, respectively. In the WAI experiment, the designated IA was 200 mm, and the irrigation duration was determined by the WAI values, meaning that higher WAI values had shorter irrigation periods. Water movement for each of the five WAI treatments was under unsaturated flow. In the IA treatment experiment, the designated WAI was 1.2 mm h^{-1}, which guaranteed salt displacement under unsaturated flow conditions.

3.2. Spatial distribution of soil water content

Fig. 3-A–C shows the spatial distribution of θ over time for different WAI. The variability of θ was not straightforward:

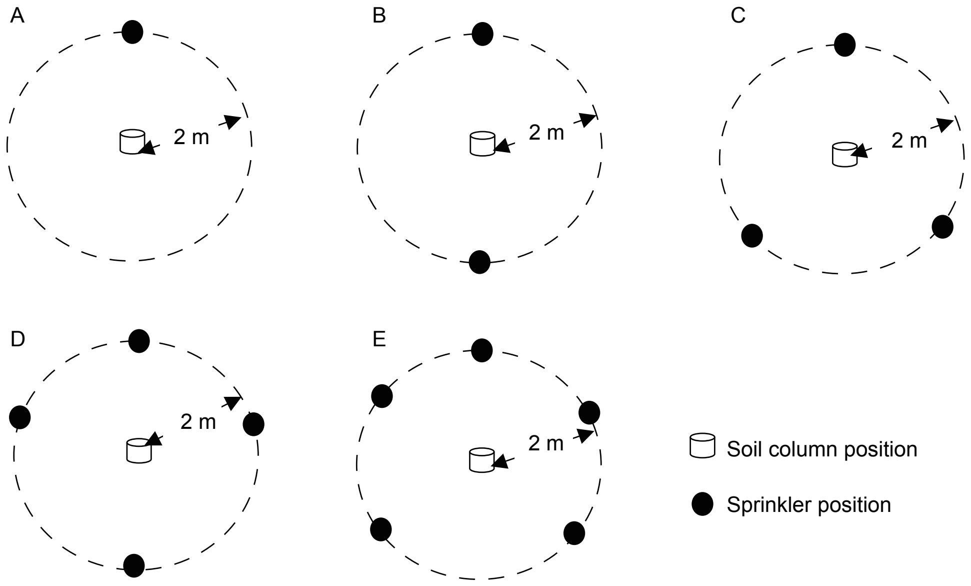

Fig. 2 Schematic maps of laboratory experiments for water application intensity treatments of 1.7 mm h^{-1} (A), 3.1 mm h^{-1} (B), 5.3 mm h^{-1} (C), 8.8 mm h^{-1} (D), and 10.1 mm h^{-1} (E).

it averaged 21.1% in the upper 20 cm of the soil, increased gradually to approximately 23.8% as soil depth increased to 20–40 cm, and then slightly decreased to approximately 20.0% at 40–60 cm in depth at 0 h of water redistribution. Water movement continued during water distribution. Compared to the results obtained at 0 h of water redistribution, slight increases of soil moisture were observed at greater depths after 24 and 48 h of water redistribution. However, no obvious treatment differences in θ were observed, as each treatment had a similar wetting pattern, with average θ values at 0–60 cm of 22.8, 22.9, 22.5, 22.5, and 22.7% for the 1.7, 3.1, 5.3, 8.8, and 10.1 mm h^{-1} WAI treatments, respectively.

Fig. 3-D–F illustrates the spatial distribution of θ for the five IA treatments. At 0 h of water redistribution, the soil water content increased and then decreased as soil depth increased. Soil moisture tended to decrease between 0 and 60 cm in depth as IA value increased. The θ over the entire soil column averaged 16.5, 18.7, 20.5, 22.3, and 24.8% for the IA values of 148, 168, 184, 201, and 223 mm, respectively, indicating that soil moisture was maintained near field capacity but with clear treatment differences. The depth regions of the respective IA treatments with the greatest moisture contents were 25–30, 30–35, 35–40, 35–40, and 35–40 cm, with θ values averaging 20.9, 21.2, 21.7, 24.5, and 30.3%, respectively. The results showed that as IA increased, the region with the greatest moisture became deeper and the highest θ value increased. Compared to the results obtained at 0 h of water redistribution, a slight decrease of soil moisture was observed in the soil profile at deeper depths after 24 and 48 h of water redistribution; the differences among the five IA treatments were not straightforward, indicating that deep percolation was likely increased.

In this experiment, θ changed with time and space, and its value increases and then decreases as soil depth increased. A relatively moist region formed in the subsoil, and only a minority of the soil water moved to the deeper layer because of the ability of the soil in the deeper layer to receive water weakened as the soil water potential gradient decreased. At 24 and 48 h after treatment, due to gravity potential and matric potential, soil water continued its movement and redistribution. The subsoil began to drain after wetting as the soil in the upper layer continued draining. Due to this redistribution of soil moisture, soil water matric potential approached equilibrium, and the variation of θ became smooth.

3.3. Spatial distribution of ECe

Fig. 4-A–C displays the spatial distribution of ECe after 0, 24

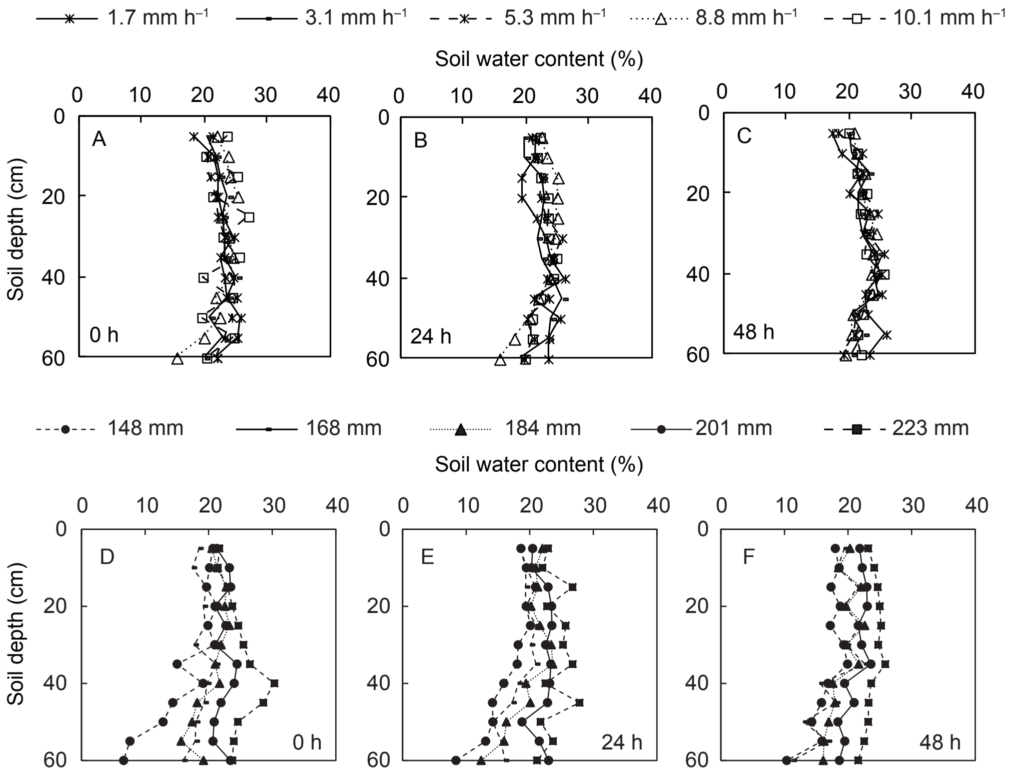

Fig. 3 The spatial distribution of soil water content at 0, 24 and 48 h after water redistribution under water application intensity treatments (A–C) and irrigation amount treatments (D–F).

and 48 h of water redistribution under the WAI treatments. Because of the surface-source nature of microsprinkler irrigation, the salts moved along with the water in all layers and decreased significantly, forming a desalinization zone. At 0 h of water redistribution, a low-salinity zone emerged at 0–30 cm. The average ECe value of the low-salinity zone was 2.2 dS m^{-1}, 90.0% lower than its original value. The highest salt concentration occurred at 50–60 cm depth in all treatments, averaging 27.3, 31.0, 38.5, 29.7, and 20.3 dS m^{-1} in the 1.7, 3.1, 5.3, 8.8, and 10.1 mm h^{-1} WAI treatments, respectively, representing respective increases of 23, 39, 73, 33, and –9% over the original values. The results indicated that higher WAI values generated better leaching effects. At 24 and 48 h of water redistribution, the zones with low ECe values had expanded in the five treatments. Much of the salt leached from the low-salinity zone accumulated in the subsoil, and some excess salt leached out of the entire soil profile. Therefore, WAI had an obvious effect on soil salinity redistribution.

Fig. 4-D–F shows the spatial distribution of ECe at 0, 24 and 48 h of water redistribution under the IA treatments. At 0 h of water redistribution, a zone of relatively low soil salinity (average ECe of 4 dS m^{-1}) had formed at 0–20 cm in each treatment. The spatial extent of the low-salinity zone increased as IA increased from 148 to 223 mm. The vertical distances of the low-salinity zones were 0–20 cm at 148 mm, 0–25 cm at 168, 184 and 201 mm, and 0–30 cm at 223 mm. At 48 h of water redistribution, the zones of low salinity significantly expanded, and the average soil salinity in the whole soil profile (0–60 cm) decreased dramatically to 15.7, 14.4, 13.9, 13.1, and 12.6 dS m^{-1} for the 148, 168, 184, 201, and 223 mm treatments, respectively.

Even in the lowest WAI (1.7 mm h^{-1}) and IA (148 mm) treatments, a low-salinitu zone (ECe<4 dS m^{-1}) could be formed at the depth of 0–20 cm. This is especially true of the other treatments with higher WAI and IA. It may therefore be concluded that very strongly saline soil can be remediated into moderately saline soil using low-salinity water (0.4 dS m^{-1}) under microsprinkler irrigation.

3.4. Salt leaching

To further estimate the effectiveness and mechanism of salt leaching for treatment, the rate of desalinzation of the whole soil profile was calculated (Fig. 5-A and B). The relationship between the rate desalinzation and the WAI was negative linear relationship, indicating that the decreased in rate of desalinzation casused by the WAI increased. It is also evident that the WAI has a large effect on soil ECe. Although the relationship between the rate desalinzation and IA was depicted by linear equations, with increasing slow slopes. The differences of the two relationships shows that it is

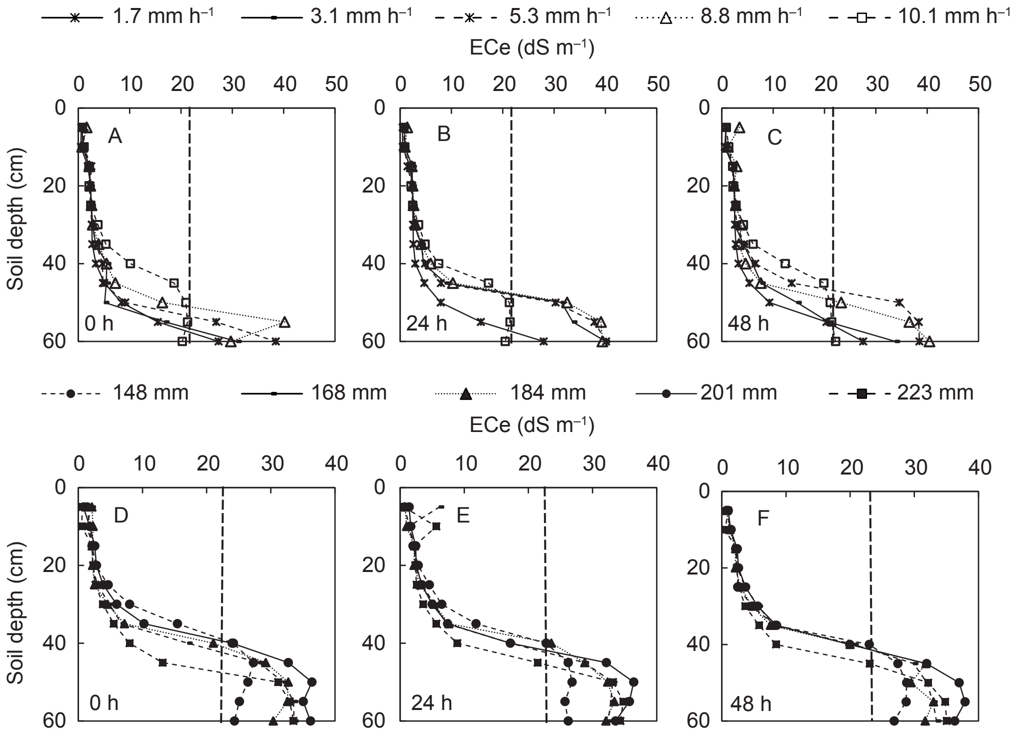

Fig. 4 The spatial distribution of saturated paste extract (ECe) at 0, 24 and 48 h after water redistribution under water application intensity treatments (A–C) and irrigation amount treatments (D–F). The ECe value of the dotted line (initial value) is 22.3 dS m^{-1}.

more effective to change WAI than WA if want to change the leaching efficiency.

3.5. Spatial distribution of SAR

The spatial distribution of SAR at 0 h of water redistribution under the WAI (Fig. 6-A) and IA treatments (Fig. 6-B) are displayed. The changes in SAR under the different treatments were similar to those of ECe. As soil depth increased, the SAR value also increased significantly.

As WAI increased from 1.7 to 10.1 mm h^{-1}, zones of relatively low SAR (average SAR of 15 (mmol L^{-1})$^{0.5}$) emerged at 40, 45, 45, 50, and 50 cm soil depth in the five respective treatments. The average SAR over the low-SAR zone was 4.9 (mmol L^{-1})$^{0.5}$, representing a decrease of 90.1% from its original value. The highest SAR values, averaging from 63.5 (mmol L^{-1})$^{0.5}$ (1.7 mm h^{-1}) to 70.4 (mmol L^{-1})$^{0.5}$ (10.1 mm h^{-1}), occurred at 55–60 cm in the soil profiles. Soil SAR was maintained at approximately 37.5 (mmol L^{-1})$^{0.5}$ at 45–50 cm and increased slightly with depth below 50 cm.

The zone of low SAR increased as IA increased from 148 to 223 mm. The vertical zone was 30 cm for the 148 mm treatment, 35 cm for the 168, 184 and 201 mm treatments, and 40 cm for the 223 mm treatment. The average low value ranged from 4.8 (mmol L^{-1})$^{0.5}$ (148 mm) to 3.7 (mmol L^{-1})$^{0.5}$ (223 mm), representing a decrease of 90.2 to 92.4% from the original value. The highest SAR occurred at 50–60 cm in depth and was maintained at approximately 68.2 (mmol L^{-1})$^{0.5}$ for IA values from 148 to 201 mm. However, the highest SAR value, approximately 39.6 (mmol L^{-1})$^{0.5}$, was observed in the 223 mm treatment, representing a decrease of 19.2% from its original value.

The results showed that the relative reductions for the SAR values were smaller than those for ECe due to the buffer capacity of the exchange (Wang *et al*. 2012). Moreover, sodium and Ca were leached to the subsoil, as was similar to the results of Qadir *et al*. (2002). In that experiment, the no-crop treatment leached more salts, Ca^{2+}, Mg^{2+} and Na^{+}

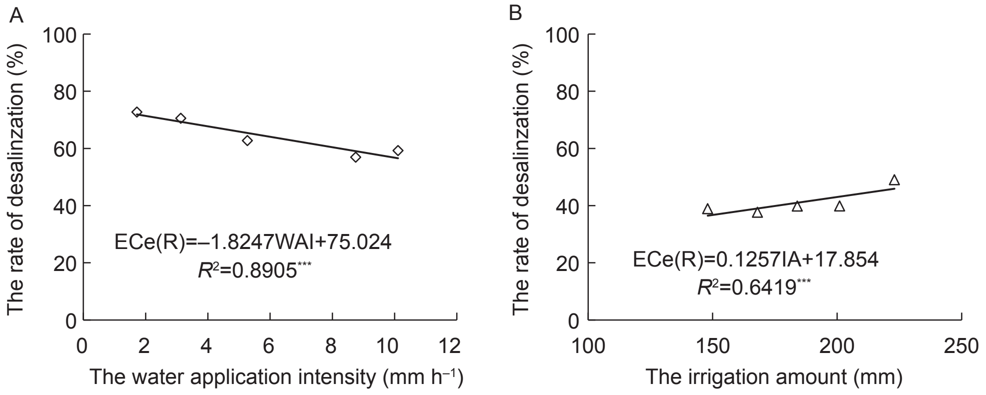

Fig. 5 The relationships between the rate of desalinztion and the water application intensity (A), as well as the irrigation amount (B).

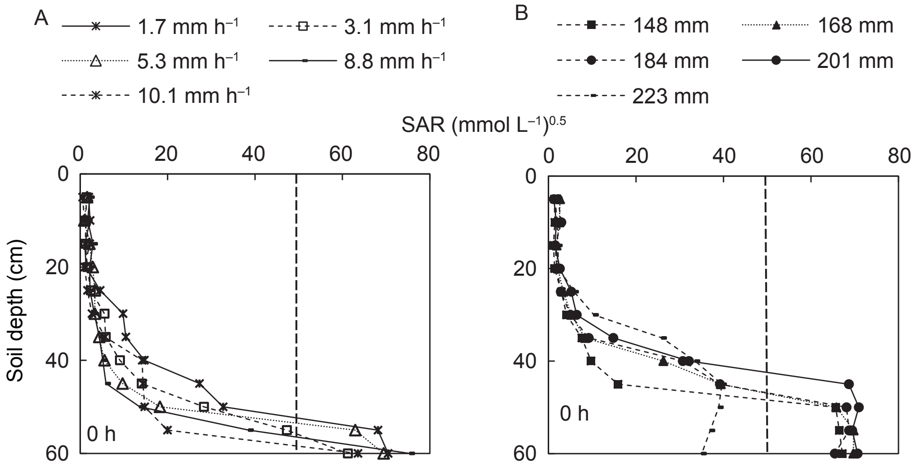

Fig. 6 The spatial distribution of sodium adsorption ratio (SAR) at 0 h after water redistribution under water application intensity treatments (A) and irrigation amount treatments (B). The SAR value of the dotted line (initial value) is 49.0 (mmol L^{-1})$^{0.5}$.

in the early stage of the study, and the removal of salts and cations decreased gradually in the later leachates due to the natural action and effective infiltration of water, which dissolved and carried away the salts while passing through the soils. Additionally, microsprinkler irrigation resulted in a greater leaching effect under the higher WAI and IA treatments.

3.6. Spatial distribution of pH

As shown in Fig. 7-A–C, the pH of the soil profile decreased for the five WAI treatments at 0, 24 and 48 h of water redistribution. The zones of higher soil pH were present primarily at 0–20 cm for the five WAI treatments at the three periods of water redistribution, and the pH was higher in the soil profiles of the 10.1, 8.8 and 5.3 mm h^{-1} treatments than in those of the 3.1 and 1.7 mm h^{-1} treatments. Compared with the initial pH (7.7), the average pH of the whole soil profile increased by 3.6, 6.9 and 8.2% for the 5.3, 8.8 and 10.1 mm h^{-1} treatments, respectively, while no obvious changes were observed for the 1.7 and 3.1 mm h^{-1} treatment. In addition, the high pH zones continually expanded for each WAI treatment, and no obvious differences in the spatial distribution were observed between the treatments at 24 and 48 h of water redistribution.

Fig. 7-D–F displays the spatial distribution of pH at 0, 24 and 48 h of water redistribution under the IA treatments. At 0 h of water redistribution, a high-pH zone emerged within the first 20 cm. The average pH of the high-pH zone was approximately 8.2, representing a 6.5% increase over its original value. The lowest pH occurred at 55–60 cm and averaged 7.5, representing a 3.0% decrease from its original value. Compared with the initial soil pH, the average pH of the entire soil profile increase is slight even in the highest IA treatment. Soil pH 8.5 was considered as field identification criterion of solonetz (IUSS Working Group WRB 2007), so it may be concluded that alkalization did not occur during salt leaching under microsprinkler irrigation. Additionally, little difference was observed due to the duration of water redistribution in each treatment.

The above results indicate that differences in WAI and IA play an important role in salt concentration but cause less obvious changes to the average pH value of the soil. For WAI values less than the maximum percolation rate of saturated soil, i.e., the soil water movement under unsaturated flow, greater WAI values are more advantageous, as are greater IA values.

4. Conclusion

The laboratory experiments were conducted using coastal saline soils from North China to explore the effects of mi-

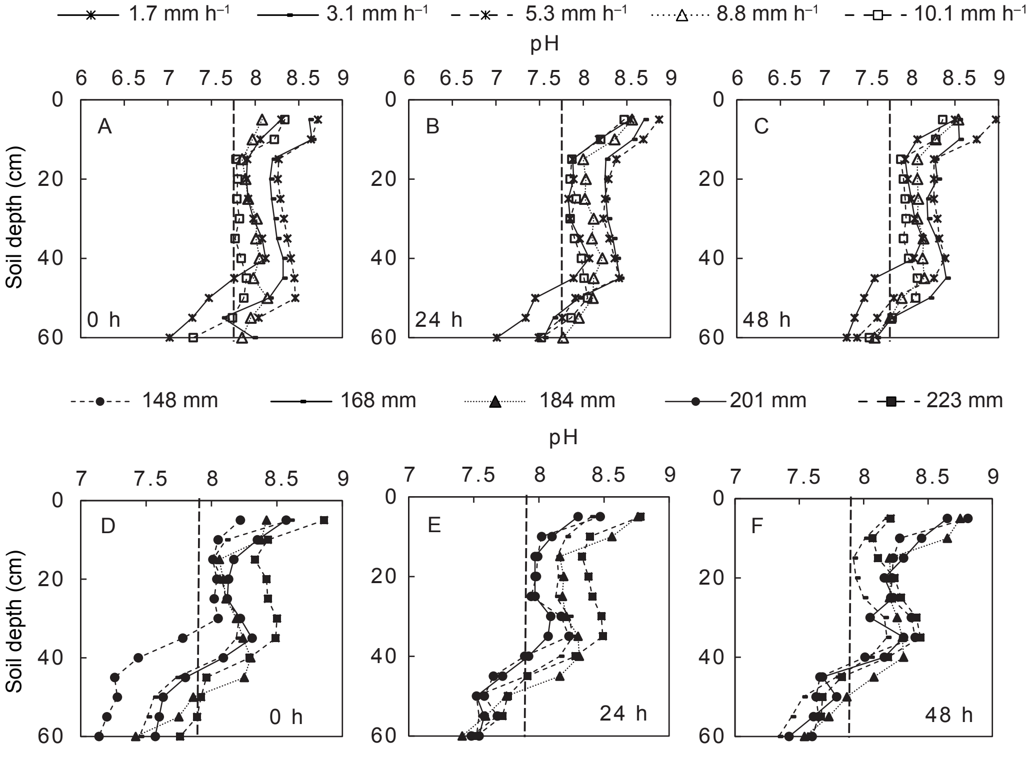

Fig. 7 The spatial distribution of pH at 0, 24 and 48 h after water redistribution under water application intensity treatments (A–C) and irrigation amount treatments (D–F). The pH value of the dotted line (initial value) is 7.8.

crosprinkler irrigation on θ, ECe, SAR, and pH under five WAI treatments and five IA treatments.

In summary, it can be concluded that as WAI increased from 1.7 to 10.1 mm h^{-1}, leaching time shortened and the variations of θ in the soil were moderated. However, the low-salt and low-SAR zone expanded as WAI increased, and the average soil salinity and SAR over the whole soil profile decreased. Additionally, the pH value increased, and its responses to WAI were reduced, as water redistribution proceeded.

As IA increased from 148 to 223 mm, leaching time lengthened, θ value increased, and the zone of low ECe, low SAR and high pH expanded. The average soil salinity and SAR over the whole soil profile also decreased, while the average pH of the profile increased. However, the variations of θ, ECe, SAR, and pH after the periods of water redistribution were not straightforward.

Taking all factors into consideration, greater WAI and IA under microsprinkler irrigation improved water movement in soils under unsaturated flow conditions, and microsprinkler irrigation is an effective method for reclaiming the highly saline soils that are widely distributed in the study area.

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