EFFECTS OF IMPROVEMENT MEASURES ON DESALTING HEAVY SALINE-ALKALI SOIL UNDER WINTER IRRIGATION IN SOUTHERN XINJIANG, CHINA

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Abstract. To identify effective improvement measures for the clay-containing interlayers of heavy saline–alkali soil in southern Xinjiang, China, this study focused on interlayer soil with heavy salinity and alkali content, examining the effects of various improvement techniques on soil salinity and desalting efficiency under consistent winter irrigation quotas from 2020 to 2023. Results showed that after the 2023 winter irrigation, following three rounds of irrigation, treatments G4, G7, G10 and CK1 reduced salinity from 11.37 to 3.35, 11.44 to 4.47, 8.81 to 1.54 and 13.50 to 7.17 $g \cdot kg^{-1}$, respectively. The G1 treatment decreased salinity from 11.25 to 1.17 $g \cdot kg^{-1}$ after four winter irrigation sessions. Among the treatments, G1 and G10 exhibited the highest desalting rates at 89.60% and 82.52%, respectively, whereas the other treatments ranged from 50.08% to 75.91%. The CK1 and CK2 treatments achieved desalting rates of 51.48% and 47.87%, respectively. These findings demonstrate that improvement measures, such as deep tillage, ditching with sand irrigation and drilling with sand irrigation, effectively reduce the salt content of heavy saline–alkali soil. These techniques significantly enhance desalting efficiency, reducing salinity to a low level after three–four winter irrigation cycles. Considering the economic feasibility and practicality of the improvement measures, drilling and sand filling are recommended for the treatment of interlayer-containing heavy saline–alkali soil in the study area.
Keywords: *winter irrigation, heavy saline-alkali soil, improvement measures, desalting effect, interannual variation of salinity*

Introduction

With the rapid development of agriculture in China, the combined effects of natural conditions and human activities are causing the expansion of saline–alkali land. This poses a serious threat to the protection of the cultivated land red line. Cultivated land is essential for food production, and food security is the nation’s most critical concern. Therefore, the comprehensive transformation and use of saline–alkali land are vital for protecting and improving cultivated land. Soil salinization is a type of “physiological drought,” where salt accumulation in the soil, driven by both natural and human factors, continuously increases soil solution concentration and osmotic pressure, making water absorption difficult for crops and, ultimately, affecting crop yield and quality.

Based on the causes of saline–alkali land, and considering the types of saline–alkali soil and salinization levels across different regions, there are several primary improvement methods: engineering improvement (Heng et al., 2022), agronomic improvement (Dilinur et al., 2020), chemical improvement (Xia et al., 2017), biological improvement (Liang, 2022) and comprehensive improvement (Xia et al., 2017). Currently, the main measures to improve heavy saline–alkali land in Xinjiang include dark pipe drainage, shaft drainage, open ditch drainage as well as other combined measures. For example, shaft drainage adjusts groundwater levels and helps to balance soil water and salt in cultivated areas. However, relying solely on shaft drainage can lead

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to salt accumulation in the middle and lower layers of the vadose zone, increasing the risks of secondary soil salinization and groundwater quality deterioration (Yang et al., 2008). Dark pipe drainage involves leaching soil with surface freshwater, allowing the infiltrated water and salt to be drawn into suction pipes, which then direct the salt-laden water to collection wells or drainage ditches. Notably, the arrangements of dark pipes influences soil salt discharge differently (Zhang et al., 2023). Open ditch drainage, commonly used for early salinized soil, also effectively discharges salt (Dou et al., 2022). The physical properties of saline–alkali land with clay interlayers create conditions of “water retention and salt suppression” (Shao et al., 2006; Lu et al., 2010, 2009), making this a key challenge in treating such land. Differences in clay interlayer texture (Lemon, 1956; Willis, 1960), position (Lu et al., 2021; Chen et al., 2021) and thickness (Xu et al., 2016) affect changes in soil water and salt. The smaller the desalting radius and the greater the thickness, will be the lower the desalting effect (Ma, 2020). To address this, the clay interlayer’s physical properties can be modified by breaking it, promoting water and salt movement. For example, when the interlayer is positioned relatively high, some scholars have drilled holes to break the clay layer and then filled them with sand, improving the desalting effect in coastal saline–alkali land. Results have shown that with an irrigation volume of 1200 $m^3 \cdot hm^{-2}$, a hole density of 30 holes$\cdot m^{-2}$ and a hole depth of 10 cm, the total desalting level is increased by 50.7%–98.8% compared with the control treatment. Increased hole density enhances the desalting effect, although the effects vary with hole depth (Zhang et al., 2017). When the clay interlayer is deep, researchers have improved it by digging pits and filling them with sand. They concluded that when the artificial pit’s minimum pore size is at least 100 cm, with hole numbers of 15, 60, 135 and 240 holes$\cdot hm^{-2}$, and an irrigation water quota of 1500–3000 $m^{-3} \cdot hm^{-2}$, the soil desalination effect is improved effectively (Ma et al., 2007).

Previous studies have shown that in improving heavy saline–alkali soils with interlayers, large-scale winter irrigation is mainly used for salt leaching during actual production (Li et al., 2014a), whereas labor-intensive methods, such as dark pipe, shaft and open ditch drainage, are less commonly applied. Additionally, biological and chemical improvements are not used for interlayers, mainly because these methods are more effective for the topsoil in crop cultivation, whereas their impact on deeper interlayers is minimal. At the same time, the saline-alkali cultivated land in southern Xinjiang has a large area and generally contains interlayers, winter irrigation causes the soil to be in a repeated state of desaline-accumulation, and the desalting effect is not good. Therefore, this study aimed to use deep digging, ditching and drilling to penetrate the deep clay interlayers. It involved analyzing the effects of different improvement measures on the salinity changes of heavy saline soil under winter irrigation conditions and determining the desalting effects of these methods. The goal was to provide fundamental data and technical support for the comprehensive management, safe and sustainable use and development of saline–alkali farmland.

Materials and methods

Overview of the study area

The experimental area is located at the high-efficiency water-saving experiment and demonstration base in Hailou Village, Hailou Town, Weigan River Irrigation Area, Shaya County, Aksu Prefecture, Xinjiang. China. In 2019, this irrigation area was designated for Shaya’s 500,000-mu high-efficiency water-saving and income-increasing

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pilot project. The core experimental site is north of Shaya County, on the west bank of the Weigan River, approximately 10 km from Shaya County. The geographical coordinates are 41°14'30" N latitude and 82°43'33" E longitude. The study area experiences sparse rainfall and a dry climate, with an average annual sunshine duration of 3031.2 h, average annual temperature of 10.7℃, average annual precipitation of 47.3 mm and average annual evaporation of 2000.7 mm.

On November 30, 2020, soil background sampling was conducted before winter irrigation, and the physical and chemical properties of the soil in the study area were analyzed in the laboratory. The study area has a clay interlayer at a depth of 60–80 cm, with groundwater at a depth of 1.9–2.5 m. According to the international soil particle analysis table, the soil texture in the study area was considered silty clay. The bulk density was 1.51–1.73 $g \cdot cm^{-3}$, the average water content was 0.066 $cm^3 \cdot cm^{-3}$ and the field water capacity was 0.35 $cm^3 \cdot cm^{-3}$. Detailed values of the soil's physical properties are presented in *Table 1*.

Table 1. *Physical property parameter values of soil in the experimental area*

Soil depth (cm)	Particle composition volume fraction (%)			Texture	Bulk density ($g \cdot cm^{-3}$)	Initial moisture content ($cm^3 \cdot cm^{-3}$)	Field capacity ($cm^3 \cdot cm^{-3}$)
	< 0.002 mm	0.002–0.02 mm	0.02–2 mm				
0–10	5.87	65.5	28.63	Silty clay	1.65	0.056	0.352
10–20	5.51	65.38	29.11	Silty clay	1.56	0.065	0.337
20–30	6.16	69.4	24.44	Silty clay	1.51	0.073	0.33
30–40	5.88	68.07	26.05	Silty clay	1.61	0.071	0.4
40–50	4.32	65.82	29.86	Silty clay	1.38	0.063	0.329
50–60	5.77	74.03	20.2	Silty clay	1.56	0.071	0.312
60–70	6.75	72.65	20.6	Silty clay	1.73	0.069	0.284
70–80	4.68	62.12	33.2	Silty clay	1.69	0.067	0.398
80–90	4.29	58.16	37.55	Silty clay	1.55	0.063	0.41
90–100	5.41	71	23.59	Silty clay	1.57	0.064	0.381

Based on the background investigation and analysis, the soil's total nitrogen was 0.47 $g \cdot kg^{-1}$, total phosphorus was 0.64 $g \cdot kg^{-1}$, total potassium was 19.76 $g \cdot kg^{-1}$ and pH was 8.74. The soil salt content exceeded 10 $g \cdot kg^{-1}$, with sulphate chloride as the dominant salt type. According to the classification standard for soil salinization in cultivated land, these findings qualify the area as heavily salinized. Specific chemical property values are shown in *Table 2*.

Table 2. *Parameter values of soil chemical properties in the experimental area*

Soil depth (cm)	Cl^- ($g \cdot kg^{-1}$)	SO_4^{2-} ($g \cdot kg^{-1}$)	Ca^{2+} ($g \cdot kg^{-1}$)	K^+ ($g \cdot kg^{-1}$)	Mg^{2+} ($g \cdot kg^{-1}$)	Na^+ ($g \cdot kg^{-1}$)	CO_3^{2-} ($g \cdot kg^{-1}$)	HCO^{3-} ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	Total P ($g \cdot kg^{-1}$)	Total K ($g \cdot kg^{-1}$)	Salt content ($g \cdot kg^{-1}$)	pH
0–10	5.91	2.40	1.07	0.14	0.97	3.46	0.00	0.13	0.72	0.86	18.7	14.09	8.7
10–20	3.30	3.24	0.99	0.09	0.80	3.15	0.00	0.12	0.55	0.77	18.6	11.68	8.7
20–30	3.03	2.97	0.51	0.05	0.54	3.53	0.00	0.15	0.60	0.70	18.6	10.79	8.7
30–40	2.50	4.43	0.59	0.08	1.01	2.11	0.00	0.15	0.60	0.62	20.1	10.86	8.7
40–50	3.89	10.30	1.93	0.12	1.16	3.65	0.00	0.13	0.45	0.61	19.6	21.18	8.7
50–60	3.63	11.64	2.66	0.08	1.82	4.16	0.00	0.08	0.53	0.59	22.4	24.07	8.7
60–70	4.71	15.12	2.95	0.11	2.48	4.47	0.00	0.13	0.43	0.55	23.3	29.97	8.8
70–80	4.67	10.36	2.54	0.08	1.96	4.35	0.00	0.09	0.27	0.62	18	24.06	8.8
80–90	4.51	8.08	1.98	0.04	1.42	3.68	0.00	0.07	0.22	0.57	17.2	19.77	8.8
90–100	4.53	5.77	1.08	0.04	1.10	3.53	0.00	0.08	0.30	0.49	21.1	16.12	8.8

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Experimental design

Design and process of the winter irrigation experiment

The winter irrigation experiment was conducted annually from late November, after the cotton harvest, to mid-December. Soil sampling occurred before and after winter irrigation, The winter irrigation quota is consistent with the irrigation level of local farmers, which is 3150 $m^3 \cdot hm^{-2}$ (Zhang et al., 2016). The specific winter irrigation schedule is shown in *Table 3*.

Table 3. *Winter irrigation experiment design*

Winter irrigation frequency	Winter irrigation date	Soil sampling date	
		Before irrigation	After irrigation
First	2020.12.04	2020.12.01	2021.01.04
Second	2021.12.10	2021.12.05	2022.01.10
Third	2022.12.02	2022.11.28	2023.01.02
Fourth	2023.12.12	2023.12.07	2024.01.16

Experimental design of improvement measures

On November 12, 2020, a background survey was conducted in typical heavy saline–alkali areas of Shaya. After sampling and analysis, a representative cotton field with heavy saline–alkali interlayer soil was selected as the test site. The cotton yield in this area had been almost ‘zero’ for the past three years, covering an area of ~0.8 ha. On November 7 of the same year, deep tillage (G1) and drilling (G2) measures were implemented. A Longong LG6060D crawler excavator was used to uniformly turn the soil layer to a depth of 1 m. For drilling, a Yamaha 159Fv four-stroke ground drill from Yingshang Xingyuan Technology Development Co., Ltd., with a 6 cm aperture, was used. The drilling density was 36 holes 100 m^{-2} (with 2 m spacing), and the holes were 1 m deep. The area of each treatment plot was 100 m^2, and drilling was repeated twice.

On March 5, 2021, before cotton sowing, four additional measures were introduced: hole drilling with sand irrigation, ditch drilling, ditch drilling and ditch drilling with sand irrigation. Three hole density gradients were set for drilling: 36 holes·100 m^{-2} (with 2 m spacing), 121 holes·100 m^{-2} (with 1 m spacing) and 441 holes·100 m^{-2} (with 0.5 m spacing). The Longong LG6060D crawler excavator was used to excavate salt drainage ditches along the test area’s edge, perpendicular to the agricultural ditch. The ditches were 1 m wide, 2 m deep and 50 m long, with 6–8 m intervals. After two flood irrigations, the salt drainage ditches were backfilled, initially excavated in September 2020 and backfilled in March 2021. Trenching and trenching were performed based on trenching, with all other parameters identical to those of trenching and trenching. The control treatment was conventional heavy saline–alkali land (CK1), with each treatment plot covering 100 m^2. The 2022 and 2023 trials followed the same protocol as those in 2021. Detailed treatment designs are presented in *Table 4*.

Determination index

Three sampling points were selected in the middle of each plot in the north-south direction, and each subsequent sampling was near the last sampling point.

Soil moisture content was determined using the drying method. Samples were taken at depths up to 100 cm, with measurements at intervals of 20 cm. After recording the

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wet weight of each sample, the soil was dried at 105℃ for 8 h, and moisture content was calculated based on the dry weight.

Soil conductivity was measured using the conductivity method. Samples were taken at depths up to 100 cm, with one layer every 20 cm. From each layer, 50 g of wet soil was collected. After air drying, 20 g of soil was passed through a 1-mm soil screen and placed in a 250-mL triangular bottle. The conductivity of the soil extract was measured using a DDSJ-308A conductivity meter. Sampling times for conductivity measurements were consistent with those for soil water content, and the soil samples used were also consistent.

Table 4. *Experimental design of improvement measures for heavy saline–alkali land*

Treatments	Improvement measure	Hole density (hole·100 m^{-2})
G1	Deep tillage	
G2	Drill holes and fill with sand	36
G3	Drill holes and fill with sand	121
G4	Drill holes and fill with sand	441
G5	Drill holes	36
G6	Drill holes	121
G7	Drill holes	441
G8	Ditching and drilling for sand	36
G9	Ditching and drilling for sand	121
G10	Ditching and drilling for sand	441
G11	Ditching and drilling	36
G12	Ditching and drilling	121
G13	Ditching and drilling	441
CK1	Ditching and drilling	
CK2	Ditching	

Data processing

Soil desalting rate refers to the percentage difference between soil salt after each irrigation and soil salt before irrigation, which can reflect the desalting effect of winter irrigation on soil salt. The calculation formula is as follows:

$$N = \frac{S_1 - S_2}{S_1} \times 100\% \qquad \text{(Eq.1)}$$

where N is the soil desalting rate (%), S_1 is soil salt content before winter irrigation ($g \cdot kg^{-1}$) and S_2 is the soil salt content after winter irrigation ($g \cdot kg^{-1}$).

The relative desalting rate of the treatment compared with the control is calculated as follows:

$$D_R = (D_G - D_{CK}) / D_{CK} \qquad \text{(Eq.2)}$$

where D_R is the relative desalting rate, D_{CK} is the desalting rate of the control treatment (%) and D_G is the desalting rate of the measure treatment (%). When $D_R > 0$, this indicates relative desalination; when $D_R < 0$, this indicates relative salt accumulation. The higher the D_R value, the better the desalination effect.

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WPS Excel 2023 was used for data organization and preliminary analysis, and Origin 2021 was employed for graphical rendering.

Results

Effects of improvement measures on salinity in heavy saline soil under winter irrigation conditions

From 2020 to 2023, soil salinity in heavy saline–alkali land showed clear changes before and after 3–4 winter irrigation cycles using different improvement measures (*Fig. 1*). As shown in *Figure 1A*, in 2020, the average salt content before irrigation for G1, G2 and CK1 treatments (refer to *Table 4* for the treatment definitions) was 11.25, 13.38 and 14.78 $g \cdot kg^{-1}$, respectively. After irrigation, the average salt content for G1, G2 and CK1 treatments was reduced to 8.50, 12.27 and 14.15 $g \cdot kg^{-1}$, respectively; thus, the salt content decreased by 2.75, 1.12 and 0.62 $g \cdot kg^{-1}$, respectively.

As shown in *Figure 1B*, in 2021, additional measures, such as different pore densities, sediment irrigation and trenching, were implemented. Despite the variations, the general trend for all treatments, except the G1 treatment, showed an initial increase followed by a decrease in salt content with soil depth after winter irrigation. Compared with the CK1 control, the average salt content in the 0–100 cm soil layer before winter irrigation for treatments G1, G2, G3, G4, G5, G6 and G7 was 5.04, 2.10, 2.11, 2.12, 1.66, 1.74 and 2.05 $g \cdot kg^{-1}$, respectively. Compared with pre-irrigation, the average increase in salt content in the 0–100 cm soil layer post-irrigation, ranked from largest to smallest, was G1 (23.39%), G4 (19.69%), G3 (16.84%), G2 (15.46%), G7 (12.22%), G6 (11.69%), G5 (9.88%) and CK1 (5.20%). Before irrigation, the average salt content in the 0–100 cm soil layer for the G8–G13 and CK2 treatments, ranked from smallest to largest, was as follows: G10 (8.81 $g \cdot kg^{-1}$) < G9 (9.34 $g \cdot kg^{-1}$) < G8 (9.66 $g \cdot kg^{-1}$) < G12 (10.33 $g \cdot kg^{-1}$) < G13 (10.35 $g \cdot kg^{-1}$) < G11 (10.83 $g \cdot kg^{-1}$) < CK2 (11.93 $g \cdot kg^{-1}$); after irrigation, the average soil salt content decreased by 18.00%, 22.47%, 22.02%, 15.73%, 16.33%, 18.65% and 10.81% in these treatments, respectively.

In 2022, after three winter irrigation cycles (*Fig. 1C*), the average salt content in the 0–100 cm soil layer decreased for the G1–G7 and CK1 treatments, in descending order, as follows: G1 (22.56%), G4 (22.36%), G3 (19.20%), G2 (18.21%), G7 (17.38%), G6 (16.85%), G5 (16.16%) and CK1 (8.18%). After irrigation, the average salt content, in descending order, was as follows: CK1 (9.35 $g \cdot kg^{-1}$) > G5 (8.27 $g \cdot kg^{-1}$) > G6 (7.75 $g \cdot kg^{-1}$) > G7 (7.41 $g \cdot kg^{-1}$) > G2 (6.89 $g \cdot kg^{-1}$) > G3 (5.45 $g \cdot kg^{-1}$) > G4 (5.05 $g \cdot kg^{-1}$) > G1 (2.71 $g \cdot kg^{-1}$). The average salt content increment in the G8–G13 and CK2 treatments after irrigation ranked as follows: G10 (24.83%) > G9 (22.76%) > G8 (21.63%) > G13 (20.04%) > G12 (19.09%) > G11 (18.71%) > CK2 (16.20%).

As shown in *Figure 1D*, the pre-irrigation salt content in the 0–100-cm soil layer for improved treatments ranged from 2.14–7.65 $g \cdot kg^{-1}$, with an average of 4.79 $g \cdot kg^{-1}$. This was 2.86 $g \cdot kg^{-1}$ lower than the control treatment's average of 7.66 $g \cdot kg^{-1}$. Similarly, post-irrigation, the average soil salinity for improved treatments was 3.72 $g \cdot kg^{-1}$, which was 2.98 $g \cdot kg^{-1}$ lower than the control treatment at 6.70 $g \cdot kg^{-1}$. After winter irrigation, the average reduction in salinity for improved treatments was 1.08 $g \cdot kg^{-1}$, compared with 0.96 $g \cdot kg^{-1}$ for the control, indicating that the improvement measures under winter irrigation conditions were effective in reducing soil salinity.

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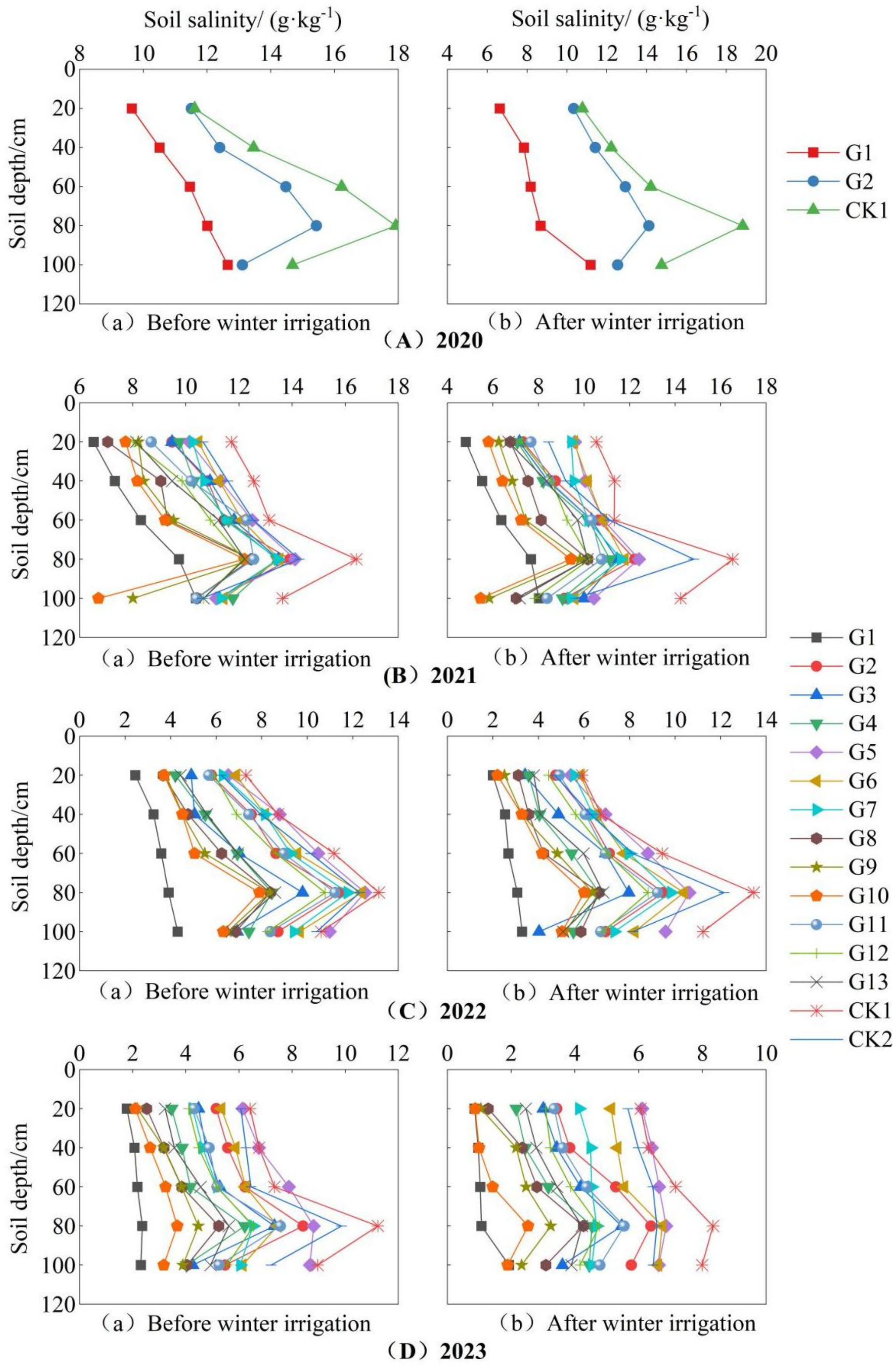

***Figure 1.** Effects of different improvement technologies on soil salinity changes under winter irrigation conditions from 2020 to 2023*

Based on this analysis of soil salt changes over 3–4 winter irrigation cycles from 2020 to 2023, the salt content in heavy saline soil was markedly reduced with the

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application of improvement technologies compared with control treatments. Both CK1 and CK2 control treatments maintained a higher salt content before and after irrigation each year. Among the different improvement techniques, the deep tillage treatment showed the greatest reduction in post-irrigation salt content, followed by the trenching and hole-and-sand irrigation techniques. Drilling with ditching as well as hole-and-sand irrigation methods produced similar favorable results, indicating that these improvement technologies effectively reduce salinity in heavy saline soil under winter irrigation conditions.

Inter-annual variation of soil salinity under different soil treatments

The inter-annual changes in soil salinity across different treatments are shown in *Figure 2*. Under winter irrigation conditions, soil salinity for all treatments decreased over the years, although each treatment exhibited distinct performance in different years. For example, soil salinity in the G1 treatment decreased after the first winter irrigation and continued to decline during the drip irrigation period (cotton growing period) (*Fig. 2a*). Following drip irrigation, during the off-cropping period for cotton, soil salinity decreased with irrigation. Subsequently, salinity increased, before decreasing again with the return of winter irrigation. This decline persisted throughout the drip irrigation and off-cropping periods in 2022. After the third winter irrigation in 2023, soil salinity increased during the drip irrigation period and decreased during the off-cropping period. These fluctuations indicate that the salinity trend varied markedly during different periods of each year. Despite this, the overall trend showed a gradual decrease in salinity across the years. For instance, the G1 treatment led to a reduction from 11.25 $g \cdot kg^{-1}$ before the first winter irrigation in 2020 to 1.17 $g \cdot kg^{-1}$ after the fourth winter irrigation: a decrease of 90%. Inter-annual data further revealed that salinity consistently declined from one winter irrigation to the next, with decreases of 29%, 59% and 39% after the first three irrigations, respectively. Similarly, other treatments demonstrated varying inter-annual changes. For example, the G7 treatment led to a decrease in salinity from the first winter irrigation until the end of the drip irrigation period, followed by a temporary increase during the harvest and off-cropping periods (*Fig. 2c*). However, salinity continued to decline from the second to the third winter irrigation. This pattern is consistent with the performance of G1 after the second winter irrigation in 2022. Treatment G4 and G10 showed consistent trends across three winter irrigation cycles, although the rate of salinity reduction varied (*Fig. 2b, d*). For instance, in the G4 treatment, salinity decreased by 43%, 33% and 23% after each winter irrigation cycle, respectively. Similarly, the G10 treatment led to salinity reductions of 38%, 46% and 48% after each cycle, respectively. By the end of the third winter irrigation, soil salinity under the G4 and G10 treatments had decreased significantly by 71% and 83%, respectively. The control treatments of CK1 and CK2 also demonstrated notable inter-annual changes in soil salinity. The trend for CK1 was consistent with that of G1, whereas CK2 showed a different trend between the first and second winter irrigation. However, the salinity reduction performance after the second winter irrigation aligned with that of G4 and G10. Overall, the CK1 and CK2 treatments reduced salinity by 51% and 48%, respectively.

Based on the inter-annual variations in soil salinity after winter irrigation across different treatments, it is clear that although all treatments received the same amount of irrigation, the resulting changes in soil salinity varied between growing and off-cropping periods. However, the general trend showed a decrease in salinity over the

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years. For example, after three winter irrigation cycles, treatments G4, G7, G10 and CK2 showed reductions in salinity of 71%, 61%, 83% and 48%, respectively, compared with pre-irrigation levels. After four winter irrigation cycles, G1 exhibited the most significant reduction in salinity.

In summary, the G1 treatment proved to have the most effective desalination effect, followed by G10 (ditch and hole irrigation) and then G4 and G7 (hole irrigation). Although the control treatments also showed reductions in salinity over the years, their reduction rates were lower. Specifically, heavy saline–alkali land could be reduced from high salinity to medium or low salinity after three times winter irrigation cycles. However, the control land remained at a moderate salinity level after three years, further underscoring the impact of improvement measures in reducing the salinity of heavy saline soil.

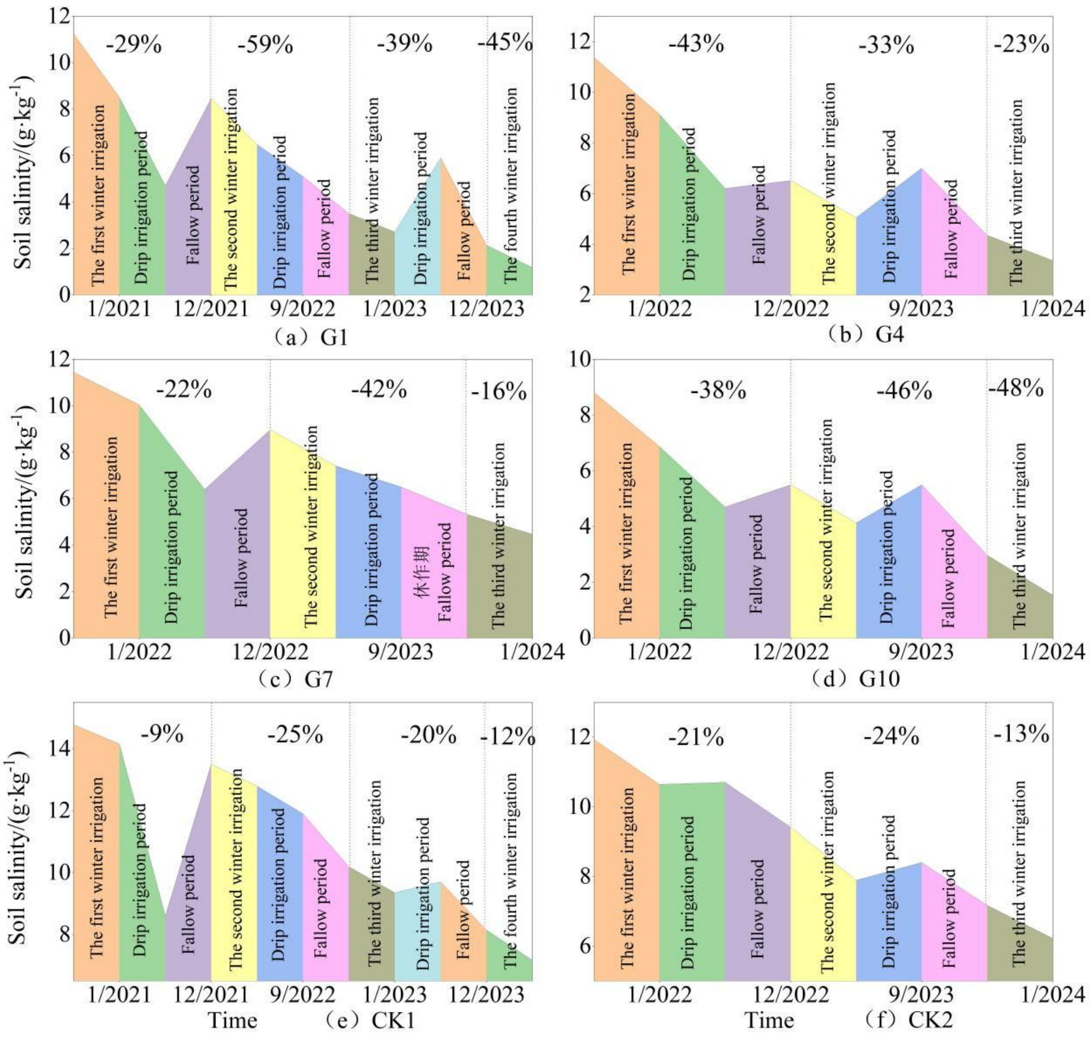

Figure 2. *Inter-annual variation in soil salinity under various soil improvement treatments*

Effects of improvement treatments on desalinization in heavy saline soil

The soil desalting effects of various treatments are shown in *Table 5*. It is evident that each treatment achieved a certain level of desalination in different years, with

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significant variations among treatments. For example, in 2020, among the three treatments applied, G1 had a significantly higher desalting rate compared with G5 and CK1. The average desalting rates for G1, G5 and CK1 were 24.93%, 8.34% and 4.67%, respectively. In 2021, with the addition of more treatments, G1 continued to exhibit the highest average desalination rate (23.65%), followed by G9 (22.61%), G10 (21.88%) and G4 (20.03%). These were followed by G13 (18.56%), G3 (17.22%), G8 (16.93%), G12 (15.95%), G2 (15.90%), G11 (15.66%), G7 (12.07%), CK2 (11.62%) and G6 (11.61%) with lower rates. Notably, the lowest desalting rates were observed for G5 and CK1 (9.60% and 5.71%, respectively).

Table 5. *Desalination rates in soil layers at distinct depths across different years and under various treatments*

Treatment	**Soil depth (cm)**					**Average desalting rate/%**
	0–20	**20–40**	**40–60**	**60–80**	**80–100**	
G1	32.05	31.29	32.53	31.31	18.68	29.17
G2	24.67	23	13.28	17.77	11.11	17.97
G3	29.27	18.03	11.47	19.69	22.76	20.25
G4	26.83	27.96	19.15	21.77	12.73	21.69
G5	8.27	11.29	13.89	14.52	11.76	11.95
G6	9.14	12.83	13.6	12.83	7.82	11.25
G7	7.49	11.76	12.63	19.52	21.35	14.55
G8	22.88	22.64	23.98	19.2	23.53	22.45
G9	36.49	26.05	23.32	24.26	29.25	27.87
G10	41.44	37.3	31.77	26.01	26.44	32.59
G11	15.88	20.42	18.14	19.56	16.04	18.01
G12	19.83	19.74	19.6	20.4	22.9	20.5
G13	18.59	20.23	17.35	20.72	25.92	20.56
CK1	10.51	12.03	11.04	4.43	0.03	7.61
CK2	17.21	15.37	10.47	10.24	13.89	13.44

Following winter irrigation in 2022, the CK1 treatment again had the lowest desalting rate (9.80%). The CK2 treatment showed slightly better performance (17.62%), which was marginally higher than that of G7 (17.12%). Among the other improvement treatments, G10 achieved the highest desalting rate (26.07%), with the remaining treatments falling within the range 18.27%–23.61%. In 2023, the G10 and G1 treatments maintained their superior performance, with average desalting rates of 49.83% and 45.85%, respectively. This was largely due to the initial soil salinity in these treatments already being lower level compared with the other treatments; thus, the reduction in soil salinity post-irrigation was more pronounced. For instance, in G1, the average salt content in the 0–100 cm layer declined from 2.14 $g \cdot kg^{-1}$ before irrigation to 1.17 $g \cdot kg^{-1}$ after irrigation. Although the absolute change in soil salinity was modest, at 0.97 $g \cdot kg^{-1}$, it still exceeded the reductions observed in other treatments, such as G6 (0.34 $g \cdot kg^{-1}$), G7 (0.86 $g \cdot kg^{-1}$) and CK1 (0.95 $g \cdot kg^{-1}$). Consequently, G1’s desalting rate was significantly higher than those of the other treatments. All treatments, except for G6 (5.27%), exhibited desalting rates ranging from 13.39% to 37.40%, which were consistently higher than those of the controls CK1 (10.25%) and CK2 (11.06%).

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By comparing the overall desalting rate and relative desalting rate of each treatment after multiple winter irrigation, it can be found (*Fig. 3*) that G1 treatment has the best desalting effect after four times of winter irrigation, with a relative desalting rate of 0.9, followed by G10 treatment with a relative desalting rate of 0.7. Although G5 and CK1 treatments were also given four times of winter irrigation, the desalting effect was not ideal, and the relative desalting rate was 0.1 and, which was only higher than that of G6 treatment. From the perspective of different improvement technologies, soil mixing techniques should be applied following the G1 treatment. Comparatively, methods such as ditching and hole irrigation (G8–G10) and hole irrigation alone (G2–G4) were highly beneficial for soil desalination. This demonstrates that deep tillage, ditching, hole drilling and sand irrigation can markedly enhance the desalination of heavy saline–alkali soil.

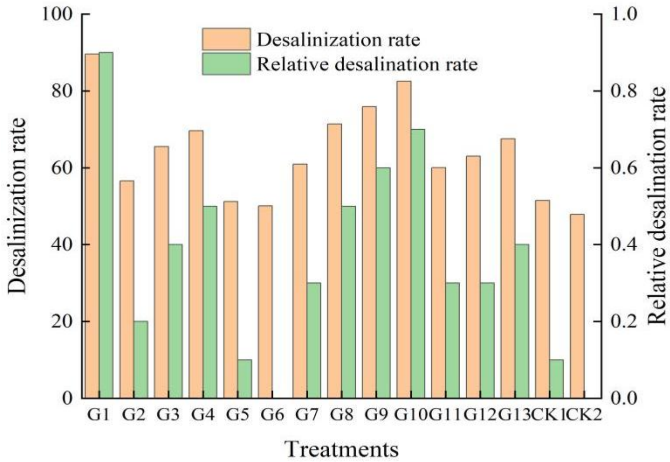

Figure 3. *Desalting rate and relative desalting rate of soil under different treatments*

Discussion

Effects of improvement measures on salinity in heavy saline soil under winter irrigation conditions

Soil salinization is a critical issue that limits the sustainable use and development of agricultural water and soil resources in southern Xinjiang, China. Winter and spring irrigation during the off-cropping period on heavy saline–alkali land plays a crucial role in influencing soil water and salt dynamics, serving as the main method for leaching soil salt. Studies have shown that in southern Xinjiang, the desalination effect increases with greater volumes of winter irrigation. Optimal winter irrigation volumes are 1800–3000 $m^3 \cdot hm^{-2}$ (Yang et al., 2016), with such irrigation significantly improving the water–salt balance in the soil. For example, when the irrigation volume exceed 3600 $m^3 \cdot hm^{-2}$, soil moisture content in the 0–100-cm layer can increase by over 20% and the desalting rate can rise by > 40% compared with pre-irrigation levels (Li et al., 2020). Moreover, the desalting effect becomes more pronounced with repeated winter irrigation cycles. For instance, after a single winter irrigation, soil salinity in the 0–150 cm layer can decrease to below 5.74, 3.00 and 4.76 $g \cdot kg^{-1}$ and between 6–60, 10–65 and 4–22 $g \cdot kg^{-1}$, respectively. After four winter irrigation cycles, the desalting rate in various soil types can exceed 63.52% (Feng et al., 2021; Chen et al., 2023).

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In the present study, a winter irrigation quota of 3150 $m^3 \cdot hm^{-2}$ was used, and significant reductions in soil salinity were observed after three winter irrigations. Prior to winter irrigation in 2020, salinity levels were 11.25–14.78 $g \cdot kg^{-1}$; by 2022, following winter irrigation, salinity decreased to 3.50–10.19 $g \cdot kg^{-1}$, with an average reduction of 42.66%. This aligns with previous findings. Among the various improvement treatments, the deep tillage treatment achieved the highest desalting rate, reaching 75.91%, whereas the other improved treatments fell within the 30.14%–55.56% range. A comparison of different improvement technology combinations revealed that deep tillage was the most effective method, particularly after three winters of irrigation. Among the other treatments following two winter irrigations, the desalting effect ranked from high to low as follows: ditching and hole irrigation, hole irrigation alone and ditching and hole irrigation, with average desalting rates of 52.37%, 49.07%, 41.40% and 33.14%, respectively, whereas the control treatment achieved an average desalting rate of 32.29%, from the above analysis, it can be seen that compared with the previous research results using only winter irrigation, the improvement measures of deep digging and ditching and drilling sand irrigation significantly reduced soil salinity.

Varying winter irrigation quotas have different effects on soil salinity. For example, when winter irrigation volumes are 150—375 mm, the salinity change rates in mildly and moderately saline land in the 0–100 cm layer can decrease from −2.50% to −15.38% and from 12.22% to −16.85%, respectively, after two winter irrigations (Lu et al., 2021). However, in the present study, only the standard local winter irrigation quota was used. After two winter irrigation cycles in heavy saline–alkali land, the improved salt change rate ranged from −9.88% to 23.39% in 2021 and from −16.16% to 24.83% in 2022. Thus, the salt change rate after improvement treatment applications in 2021 and 2022 was −15.75% and −18.94%, respectively, indicating that this rate increased as the number of winter irrigations increased following the improvement measures.

Effects of improvement measures on inter-annual salinity changes in heavy saline soil under winter irrigation conditions

Winter irrigation has proven to be highly effective at leaching soil salts from the top 60 cm of soil, although it has a limited effect on deeper salt deposits, sometimes even resulting in salt accumulation at greater depths. In spring, due to strong evaporation and limited infiltration depth, spring irrigation primarily washes away salts from the surface layer, particularly within the top 20 cm of soil (Li et al., 2014b). Winter irrigation, in contrast, not only removes substantial quantities of soil salts but also increases soil moisture content, which reduces the upward migration of deeper soil water and groundwater during freezing periods. This process inhibits the accumulation of surface salts during freeze–thaw cycles in the off-cropping period (Hu et al., 2015).

Hu et al. (2015) explored the inter-annual soil salt changes under winter irrigation conditions over a six-year period. Their study revealed that soil salinity decreased during winter irrigation but increased during the off-cropping period, further increased at the seedling period, decreased during the drip irrigation period and then increased again at the harvest stage. This pattern of salt change varied annually and interannually, depending on the irrigation methods used. In the present study, the salt change process was analyzed in a drip-irrigated cotton field with heavy salt and alkali levels after three–four winter irrigation cycles. Although all treatments showed an overall downward trend in soil salinity over the years, there were differences in salt changes at each growth stage and after each winter irrigation. For example, after the first winter

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irrigation, only CK2 treatment showed a decrease in salt during the off-cropping period, while other treatments showed a decrease in salt during the growth period and an increase during the off-cropping period. After the second winter irrigation, G1, G7 and CK1 showed a downward trend from the third winter irrigation, while G4, G10 and CK2 showed a downward trend from the third winter irrigation to the end of the growth period and the rest period. From the above analysis, it can be seen that there are significant differences with previous research results in the change of salt in off-cropping period, and the difference in salt change of different treatments in off-cropping period is mainly caused by the difference in groundwater level caused by the difference in topography after irrigation. However, groundwater level is not analyzed as the main factor affecting the change of soil salt in this paper. Further analysis and research will be carried out according to the influence of salt change on groundwater table.

At the same time, it can be seen that the overall salt change of each treatment after winter irrigation is consistent with the results of previous studies, that is, it shows a decreasing trend. For example, after 2023 winter irrigation, G1, G7 and G10 decreased from 3.50 $g\cdot kg^{-1}$, 8.97 $g\cdot kg^{-1}$ and 5.50 $g\cdot kg^{-1}$ to 1.17 $g\cdot kg^{-1}$, 4.47 $g\cdot kg^{-1}$ and 1.54 $g\cdot kg^{-1}$, respectively, and after 3-4 times of winter irrigation, the salinization level was reduced from moderate to moderate. The control treatment still treated the moderate salinization level, which further indicated that winter irrigation combined with improvement technology had a good leaching effect on soil salinity, but the mechanism of improvement measures on soil salinity needs further study.

Effects of improvement measures on desalting in heavy saline–alkali soil under winter irrigation conditions

To address the challenges of salt stress and accumulation in salinized soil, flood irrigation has traditionally been a key method for soil desalination in Xinjiang. However, improper irrigation practices and quotas used during winter and spring often lead to a cyclical pattern of salt leaching followed by re-accumulation in the 0–60-cm soil layer of cotton fields during the growing season. Indeed, the highest salt accumulation typically occurs between 40 and 60 cm (Dilinur, 2020). When comparing the desalting effects of winter and spring irrigation, research has shown that winter irrigation leaches salts to a depth of 60 cm, although it has limited impact on deeper salt layers. Conversely, spring irrigation is mainly effective on the top 20 cm of soil, and due to high evaporation and minimal infiltration, it is generally less effective than winter irrigation (Li et al., 2014b). For example, under spring irrigation, when the irrigation quota is 1350 $m^3\cdot hm^{-2}$, 1800 $m^3\cdot hm^{-2}$ and 2250 $m^3\cdot hm^{-2}$, the surface salt can be washed to 10-50 cm, 30-60 cm and 40-80 cm in low, medium and high salinized cotton fields, respectively (Li et al., 2020). As observed in studies of autumn irrigation quotas (Peng et al., 2014; Meng et al., 2002), increasing the amount of irrigation beyond a certain threshold does not always enhance soil desalination. Excessive water can raise the groundwater table, which can cause secondary salinization after irrigation (Mermond et al., 2005; Letey et al., 2007).

Improvement measures have been shown to markedly enhance soil desalinization. For example, in a study conducted in the 141st Regiment of Xinjiang, it was found that a dark drainage pipe spacing of 15 m was more effective than spacings of 20 or 25 m. The soil desalting rates were 86.47%, 85.15% and 84.01% in the horizontal direction compared with those from dark drainage pipes at 0, 5.0 and 7.5 m configurations, respectively. Moreover, the narrow spacing also led to better salt leaching compared to configurations with 20 and 25 m spacing (Wang et al., 2022). Open ditch drainage, a

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common measure for early saline soil management, has also proven to be effective. Studies have shown that it can increase desalting rates to 34.54% in the 0–20-cm layer, with this reduction rate being 12.90% and 15.58% higher than those in the 20–40- and 40–100-cm layers, respectively (Dou et al., 2022).

Due to the high potential for re-salinization in saline–alkali soil, a combination of improvement measures is often necessary for effective management. For instance, the combination of “salt drainage ditches + desulfurization gypsum + deep tillage,” can markedly reduce both the main salt ion content and pH value in the 0–100-cm soil layer (Xia et al., 2017). Similarly, “deep tillage in silt ridges + open ditch drainage” has been shown to increase soil nutrient availability, promote crop growth and increase crop yield (Gong et al., 2022). The coordinated use of “dark pipe drainage + shaft drainage” can increase water displacement by 119% compared with dark pipes alone while also reducing deep soil leakage and lowering soil salt content by 29.2 $g\cdot kg^{-1}$ at a depth of 0–80 cm after five years (Heng et al., 2022).

The effectiveness of improvement measures for saline–alkali land varies by region, emphasizing the need for localized approaches based on the specific conditions, influencing factors and causes of salinization. In the present study paper, with a winter irrigation volume of 3150 $m^3\cdot hm^{-2}$, marked improvements in desalting effects in heavy saline–alkali soil were observed compared with control treatments. The highest desalting rates were achieved using the G1 and G10 treatments (89.60% and 82.52%, respectively), with the other improvement treatments also performing relatively well (50.08%–75.91%) relative to the CK1 and CK2 controls (51.48% and 47.87%, respectively). The higher desalting rate in CK1 compared with the G6 treatment is attributed to CK1 undergoing more than one winter irrigation cycle. These results were consistent with previous studies, it shows that the improvement measures for saline-alkali land are different in different regions, and the improvement and treatment of saline-alkali land should be based on the actual situation, and according to regional characteristics, influencing factors and causes, regional treatment and local policies. This paper only analyzes the effect of improvement measures on soil desalting. However, more in-depth and systematic studies are needed on the sustainability of soil desalting effect and desalting mechanism.

Conclusion

There were significant differences in soil salt content and desalting effectiveness among various treatments after 3–4 winter irrigation cycles from 2020 to 2023. The desalting effect of deep-turning treatment was the best, from the initial severe salinization level to the low level, followed by trenching and drilling sand irrigation and drilling sand irrigation, while the control treatment remained at the moderate salinization level after 3-4 times of winter irrigation.

From the perspective of soil desalting effect under different improvement combination measures, under the same winter irrigation quota, the improvement measures can significantly improve the desalting effect of heavy saline-alkali soil, among which deep-turning measures have the best desalting effect, followed by ditching and drilling sand irrigation measures and drilling sand irrigation measures. However, considering the economic applicability and operability of each improvement measure, it is suggested that the improvement measure of drilling sand irrigation should be adopted in the heavy saline-alkali soil with the depth of interlayer 60-80 cm.

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