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Saline-alkali migration in soda saline soil based on sub-soiling technology

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ABSTRACT

Objective: To study the saline-alkali migration law of soda saline-alkali soils based on sub-soiling technology, improve the soil quality of soda saline-alkali agricultural area, and provide scientific basis for the construction of high and stable yield fields of crops in soda saline-alkali soils. Based on the unsaturated soil water movement theory and the convection–dispersion theory of solute transport in porous media, a single-parameter and two-parameter model of saline-alkali transport was constructed to analyze the distribution of saline-alkali concentration in soil solution with the depth of soil layer. Soil samples were taken from four soda saline-alkali soils in different periods under sub-soiling tillage. The experimental data of soil saline-alkali content were obtained, and the law of saline-alkali migration was analyzed. When the depth was 60 cm, the content of saline-alkali in the soil before breaking the plough bottom was 0.4%, and the content of saline-alkali was 0.35% after breaking the plough bottom with sub-soiling technique. It can be seen that sub-soiling technique can promote saline-alkali infiltration and reduce the content of saline-alkali in the planting soil layer. The average water content of the sub-soiled soil was 23.4%, which was significantly higher than that of the sub-soiled soil. The soil salinity and alkali content in 100 cm depth layer decreased by 30.8%, and that in 40 cm depth layer decreased by 57%. The salinity and alkali data in different regions showed that the soil salinity and alkali content in the soil decreased by 30.8%. Saline-alkali data from different regions show that due to sub-soiling, salt-alkali in the soil moves upward, salt-alkali in the lower part of crop roots moves outward, and salt-alkali in the soil moves away from the crop root zone; between 0 and 50 cm under the soil, the content of soil salt and alkali is from small to large, forming a desalination area of saline and alkali content; sub-soiling tillage makes 0–30 cm layer soil desalinization rate reach 83.5%, the soil salt removal rate of 0–60 cm layer reached 79.9%; The effect of sub-soiling on soil salinity is less than 1.634% of the initial value.
Conclusion: sub-soiling technology can effectively reduce saline alkali content and increase crop yield in soda saline alkali soil.

Keywords: Sub-soiling technology; Saline-alkali soil; Salt and alkali transport; Law; Mathematical model; Drip irrigation infiltration

1. Introduction

Alkaline earth is a kind of soil widely existed on the earth. It is also an important land resource. At present, there are about 1 billion hectares of saline-alkali soils in the world, and about 100 million hectares in China. The area of soda-alkali land in Songnen Plain alone is 3.8 million ha, which is one of the three major soda-alkali areas in the world [1]. Saline-alkali soil in China is mainly distributed on Songnen Plain and is a land resource with great development value. In the 1960s, China put forward that planting crops is an important way to improve saline-alkali soils and increase grain yield rapidly [2].

Omni-directional sub-soiling technology is one of the key popularization projects of the “Ninth Five-Year” Plan of the State Science and Technology Commission [3–6]. It has the ability to break the plough bottom, increase the active soil layer, effectively accept natural precipitation, reduce soil salt-alkali bulk density, and improve soil water storage and

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moisture conservation. It is one of the mechanized farming practices to improve soil quality and increase grain yield in soda saline-alkali agricultural areas [7]. The application of sub-soiling technology in saline-alkali areas can save irrigation water and improve water use efficiency. Therefore, sub-soiling technology is called soil reservoir project by farmers in the beneficiary areas [8].

Taking the soda saline-alkali area of a province as the experimental site, this paper carried out the corresponding experimental research aiming at the existing problems, distribution characteristics, and the impact on agricultural and animal husbandry production in the soda saline-alkali area, which can provide scientific basis for the construction of high and stable yield fields of crops in the soda saline-alkali area and provide scientific basis for the study of planting technology in the soda saline-alkali area [9–12]. At the same time, it has important theoretical and practical significance for promoting the implementation of grain production capacity strategy and ensuring food security in China.

2. Materials and methods

2.1. Mathematical model of salt and alkali transport

Assuming that the soil is homogeneous and isotropic, solute moves completely with water, ignoring dispersion and adsorption, and water flow follows Darcy's law, an equivalent hemispheric model of point source solute for drip irrigation is proposed. It is based on Darcy's law and water continuity equation, through a series of transformations and introducing dimensionless variables, the solute continuum equation and concentration equation can be obtained [13]. A hemispheric equivalent model was used to study the solute distribution near drip irrigation point source, saturated area and root adsorption [14].

Based on the unsaturated soil water movement theory and the convection and dispersion theory of solute transport in porous media, a mathematical model of solute transport in soda saline-alkali soils was established [15]. Under the assumption of homogeneous porous media and steady flow, when only the physical exchange process of soil is considered, the saline-alkali solute transport between soil pores obeys the convection–dispersion equation [16,17]. The three-dimensional axisymmetric transport equation is as follows:

$$\frac{\alpha(\theta C)}{\alpha Z} = \frac{\alpha}{\alpha r}\left(\theta D\frac{\alpha C}{\alpha r} + \theta D\frac{\theta \alpha C}{\alpha Z}\right) + \frac{1}{r}\left(\theta D\frac{\alpha C}{\alpha r} + \theta D\frac{\theta C}{\alpha Z}\right) + \frac{\alpha}{\alpha Z}\left(\theta D\frac{\alpha C}{\alpha Z} + \theta D\frac{\theta C}{\alpha r}\right) - \left(\frac{\alpha q_r C}{\alpha r} + \frac{q_r C}{r} + \frac{\alpha q_z C}{\alpha Z}\right) \quad (1)$$

C is the concentration of soil saline-alkali solute; q_r and q_z are the radial and vertical components of soil water flux; D and Z are the hydrodynamic dispersion coefficients; θ, α, and r are the components of the hydrodynamic dispersion coefficient tensor.

The vertical one-dimensional water infiltration model is composed of the following formula:

$$q_r = \frac{K_s}{1 - e^{\frac{rz\alpha}{\theta}}} \quad (2)$$

$$\theta = \frac{q(z_f)[K_s - q(z)]e^{\frac{rz\alpha}{\theta}}}{K_s} \quad (3)$$

$$I = \int_0^{z_f} (\theta - \theta_r) Dz \quad (4)$$

Here Z is the depth of the soil, K is the salt content of the soil surface, and I is the cumulative infiltration [18]. According to the test, the measured value is basically consistent with the calculated value, only in the humidity peak, does not affect the judgment. The single parameter model of saline-alkali migration is:

$$C = C_0 \times e^{rze^{uv}} \quad (5)$$

Here C is the concentration, while C_0 is z = 0, u and V are the parameters, and the two-parameter model of salt transport is as follows [19]:

$$C = C_0 \times e^{Az^2 + Bz} \quad (6)$$

Here A and B are soil parameters. The above model shows the distribution of saline-alkali concentration of soil solution with soil depth at any time. The measured values are in good agreement with the theoretical values, which can well reflect the law of soil saline-alkali concentration movement [20].

2.2. Soil conditions

The experimental site is selected in a county, which is one of the famous poor eight counties. The land is all soda saline-alkali soils of different degrees. Soil salinity ranged from 0.2% to 0.6%, and shallow groundwater salinity ranged from 2.0 to 10.0 g L^{-1} [19]. Soil and groundwater salinity were mainly composed of chloride-sodium-magnesium type, as detailed in Table 1.

The soil density of 0–60 cm was 1.39 g cm^{-3}, the field water holding rate was 21.9%, the pH value was 8.4, and the total salt was 3.58%. The test plot was well water irrigation. The soil particle composition of 0–30 cm is shown in Table 2. Soil organic matter content of 0–30 cm was 0.934%, total nitrogen was 0.038%, total phosphorus was 0.141%, alkali-hydrolyzed nitrogen was 33.3 mg kg^{-1}, available phosphorus was 9.8 mg kg^{-1}, and available potassium was 245 mg kg^{-1}, indicating that soil fertility was not very low [21,22]. Salt content is high and belongs to heavy saline-alkali soil. The content of coarse sand and fine sand is higher, which belongs to silty loam [23].

2.3. Methods

The experiment is divided into four parts, namely, four treatments:

A: The first plot of land is 2.2 mu. The plough bottom is broken by sub-soiling technique. The plough is shallowly plowed 18 cm in front. The depth of sub-soiling is 10 cm

Table 1
Laboratory soil analysis results

Depth (cm)	Texture	pH	Salt content (%)	Organic matter (%)	Hydrolytic nitrogen (ppm)	Available phosphorus (ppm)	Capacity (g cm^{-3})	Permeability coefficient (K)
0–10	Light loam	7.4	0.26	0.74	48.6	8.8	1.38	12.24
10–20	Light loam	7.4	0.19	0.72	47.8	8.8	1.42	12.38
20–40	Light loam	7.2	0.18	0.46	40.6	6.4	1.41	8.86
40–60	Sandy loam	7.4	0.18	0.41	26.4	2.3	1.26	16.77
60–100	Medium loam	7.6	0.28	0.26	20.1	4.6	1.42	10.44

Table 2
Soil particle composition

Particle size/mm	Content/%
1–0.25	0.46
0.25–0.05	14.98
0.05–0.01	37.2
0.01–0.005	9.1
0.005–0.001	38.56

and the total is 28 cm. After the sub-soiling, the amount of crushed wheat straw is 150 kg mu^{-1}. After leveling and plowing, cotton was planted on April 25th.

B: The second acre is 30 mu. Shallow ploughing, sowing cotton on April 25th, deep interplanting on June 14th, the depth is 25 cm.

C: The third acre is 1.7 mu. Deep ploughing 25 cm on April 24th; leveling and raking, and sowing cotton on April 25th.

D: The fourth acre is plots of 20 mu, as the control plot.

In the above four treatments, water is uniformly distributed before planting and uniform planting is done, and field management is the same. During the experiment, four saline-alkali soils were sampled in different periods, and the experimental data of soil salinity and alkali content were obtained.

3. Results

3.1. Promoting saline-alkali infiltration

As a result of breaking the plough bottom, A, B, and C all have the effect of promoting precipitation infiltration, reducing surface runoff. The influence of sub-soiling on precipitation infiltration can be seen in Table 3. From the table, the infiltration amount on July 24 is 80.8 mm, July 30 is 74.7 mm, August 14 is 68.6 mm, and the infiltration rate is 100%. Under the condition of water shortage, increasing the amount of rainfall infiltration is of great significance. The amount of saline and alkali in the soil during summer rainfall, with the rainfall infiltration, the rainfall infiltration is more and more deep; the corresponding salt infiltration is also deep. According to the calculation process of the salt and alkali transport model in this paper, using sub-soiling technology to break the distribution of saline and alkali before and after the plough bottom as shown in Figs. 1 and 2.

As can be seen from Figs. 1 and 2, when the depth is 60 cm, the content of saline-alkali in the soil was 0.4% before breaking the plough bottom, 0.33% after breaking the plough bottom with sub-soiling technology, 0.42% before breaking the plough bottom, and 0.35% after breaking the plough bottom with sub-soiling technology. Therefore, sub-soiling technology can promote salt-alkali infiltration, reduce the salt-alkali content of planting soil layer, and improve crop yield.

3.2. Inhibition of spring reverses salinization

The law of saline-alkali migration in soil is as follows: saline-alkali comes with water, saline-alkali goes with water, and saline-alkali stores after water desalination [24]. According to the characteristics of water movement in this area, spring is the peak season for returning salt and alkali. The average soil water content of treatment A was 23.4%, which was significantly higher than that of other plots. Because of more water infiltration and less increase, the amount of saline-alkali in soil is also significantly lower than that in other plots. The distribution of saline-alkali in

Table 3
Effect of sub-soiling on rainfall infiltration (mm)

Handle		A	B	C	D
July 24th (precipitation 80.8)	Infiltration quantity	80.8	80.8	80.8	66.7
	(%)	100.0	100.0	100.0	82.6
July 30th (precipitation 74.7)	Infiltration quantity	74.7	68.0	74.7	50.9
	(%)	100.0	91.0	100.0	68.1
August 14th (precipitation 68.6)	Infiltration quantity	68.6	56.4	64.4	59.8
	(%)	100.0	82.2	93.4	87.2

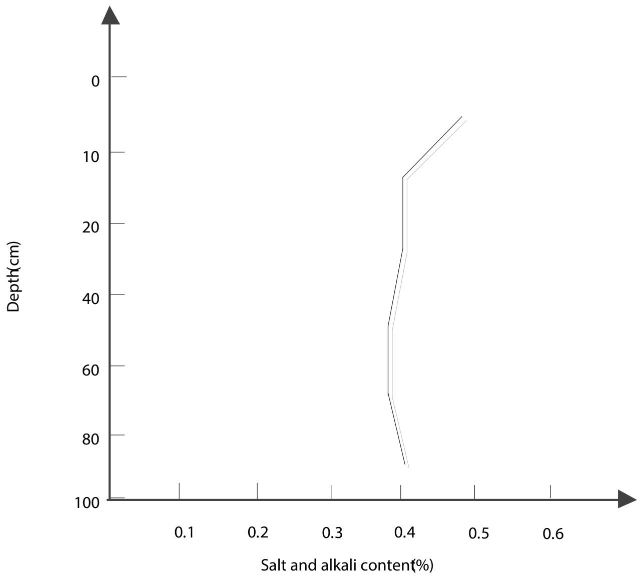


Fig. 1. Breaking the distribution of salt and alkali before plough bottom.

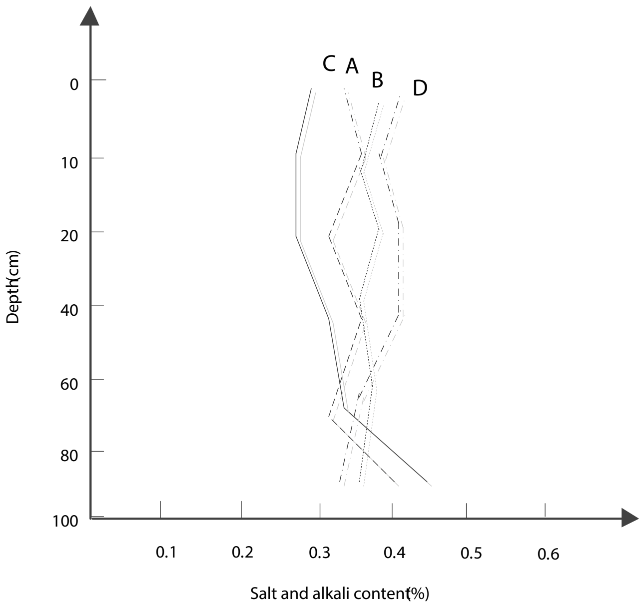


Fig. 2. Distribution of salt and alkali after breaking the plough base with sub-soiling.

different treatments is as shown in Fig. 3. When the depth is 40 cm, the amount of saline-alkali in soil treated by A is 0.25%, which is significantly higher than that of 0.3%, 0.35%, and 0.38% in other treatments. It can be seen that the sub-soiling technology enhances the soil water resistance and suppresses the salt and alkali in spring. The water barrier effect of the deep soil is shown in Table 4.

3.3. *Soil salinization after sub-soiling cultivation*

Soil salinity and alkali were selected according to the network distribution. Nine profiles were selected, each

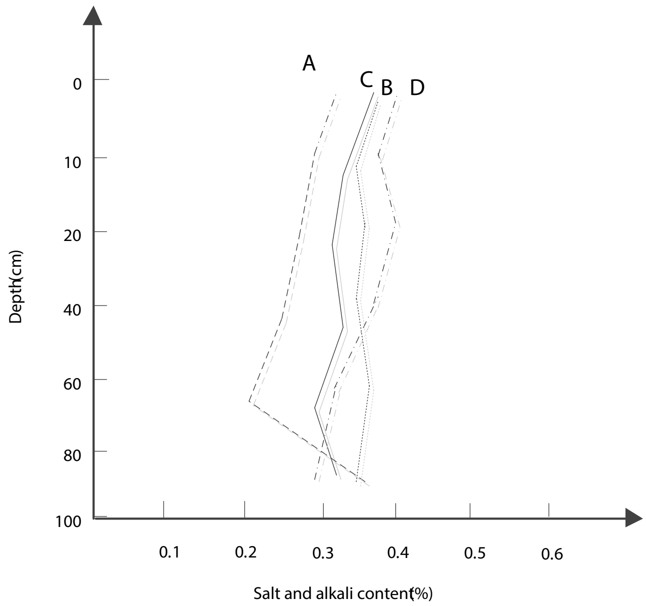


Fig. 3. Salt and alkali transport in different treatments.

Table 4
Water isolation function of sub-soiling (%)

Depth (cm) Handle	0–20	20–40	40–60	60–100	Average
A	18.4	24.1	25.2	26.2	23.4
B	19.1	22.4	23.4	24.4	22.3
C	18.6	21.8	22.6	23.8	21.7
D	18.7	21.2	22.1	23.4	21.3

of which was 1 m deep and six layers were sampled [25]. The distribution of soil salinity and alkali is shown in Table 5. From Table 5, it can be seen that 0–5 cm soil salinity is the highest in barren saline-alkali soils, and 5–15 cm soil salinity is lower than that in the upper layer. This is due to the evaporation of water into the surface layer, 15–25 cm, 25–40 cm soil salinity changes in different points, some section points than the upper layer increased, and some decreased. The soil salinity and salinity decrease from the upper level, indicating that 40 cm above is the saline-alkali active layer under natural conditions. Soil analysis was carried out before and after harvest, and salt depth data at different depths are shown in Table 6.

Because of the fine soil particles about 40 cm from the ground, the soil porosity is small, and the soil moisture content is low, which prevents the water and salt from moving down, the soil salinity above 40 cm in the barren saline-alkali soils is higher than that in the lower layer. As a result of sub-soiling, soil boundary evaporation conditions changed, sub-soiling blocked the air–soil interface, greatly reducing surface evaporation, cutting off the power of saline-alkali ascent, while continuous irrigation of crops leaching down the saline-alkali. Table 6 shows that 1 year after sub-soiling, soil salt began to accumulate below 60 cm apart, which alleviates the harm of salinization to crop roots.

Table 5
Saline alkali soil content in abandoned land

Section number	0–5 cm	5–15 cm	15–25 cm	25–40 cm	40–60 cm	60–100 cm
1	3.4	2.78	2.98	3.01	2.4	1.53
2	4.52	3.19	3.21	3.15	2.41	1.43
3	2.83	2.51	3.32	3.44	2.71	1.55
4	6.18	2.65	3.71	3.63	2.77	2.41
5	4.8	3.46	3.37	3.19	3.28	1.85
6	4.39	3.24	3.17	2.69	1.98	1.33
7	3.62	2.07	2.24	1.87	2.25	1.41
8	4.33	2.91	2.53	2.61	2.17	0.98
9	3.63	2.05	2.19	2.61	2.18	1.62

Table 6
Soil salinity and salinity after 1 year of sub-soiling cultivation

Soil depth, cm	Uncultivated land	1 year after sub-soiling cultivation
0–5	4.19	2.17
5–15	2.76	1.57
15–25	2.97	1.28
25–40	2.91	0.89
40–60	2.46	0.54
60–100	1.56	2.35

3.4. Soil total salt and alkali change in farming layer and root activity layer

According to the mathematical model of saline-alkali transport, the total saline-alkali content in 100 cm depth layer decreased by 30.8%, and that in 40 cm depth layer decreased by 57%. After 1 year of sub-soiling improvement, the salinity and alkalinity of soil tillage layer and root active layer decreased significantly, the distribution, density, and depth of soil salinity and alkalinity were shown in Table 7. It can be seen that with the depth of soil salinity gradually decreased, alkali content decreased, soil density increased, indicating that sub-soiling technology effectively improved the quality of saline-alkali soils.

3.5. Law of soil salt and alkali transport during sub-soiling

The soil for the sub-soiling test plot is taken from the earth, and the depth of the soil is 0–40 cm. The distribution of salt and alkali in the four tests is shown in Figs. 4 and 5.

As can be seen from Figs. 4 and 5, the soil salinity in area 1 is the highest, followed by area 2, and the salinity content in areas 3 and 4 is the lowest. The amount of alkali decreased, indicating that the middle salt and alkali migrated upward, and finally increased after irrigation, indicating salt accumulation.

Relative to area 1, the content of salt and alkali under seedlings (regions 2, 3, 4, and 5) was less. Before irrigation on July 21, the content of salt and alkali in the surface soil was higher. After irrigation, the salt and alkali in the soil under seedlings moved down, and the salt and alkali in the surface soil decreased. Because of sub-soiling, salt and alkali in the lower part of crop roots migrate outward, creating a good water and salt environment for crop root growth area, conducive to growth, reducing the degree of salt and alkali damage to crops. From the total salinity of the whole section, the total salinity of the soil changed little after the first irrigation and the last irrigation, which indicated that the salinity in the soil moved in the soil, but because of the regulation of sub-soiling, the salinity and alkali were far away from the root area of crops, and the crops could grow normally.

3.6. Vertical migration of saline-alkali soil under sub-soiling conditions

Under the condition of sub-soiling, the saline-alkali in the soil is transported vertically by water leaching. At first, a desalination-alkali area is formed under the effluent dripper, then a saline-alkali accumulation area is formed under it, and a high salinity-alkali area is formed near the wetting peak. The saline-alkali content of the area is higher than the initial salinity-alkali content of soda saline land. Soil salinization under sub-soiling conditions is shown in Table 8.

Table 7
Soil salinity distribution density and depth of soil layer

Depth of each layer	Salt and alkali content in first year/%	Salt and alkali content in second year/%	Soil density/(g cm^{-3})
5	4.19	2.17	1.18
10	2.76	1.57	1.258
15	2.97	1.28	1.3
20	2.91	0.89	1.35
30	2.46	0.54	1.5
40	1.56	0.35	1.5

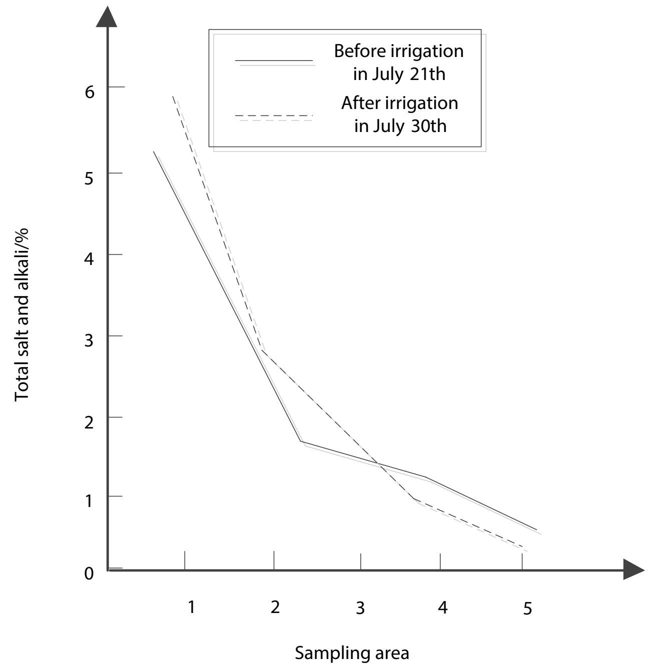


Fig. 4. Distribution of total salt and alkali before and after irrigation on July 21st and 30th.

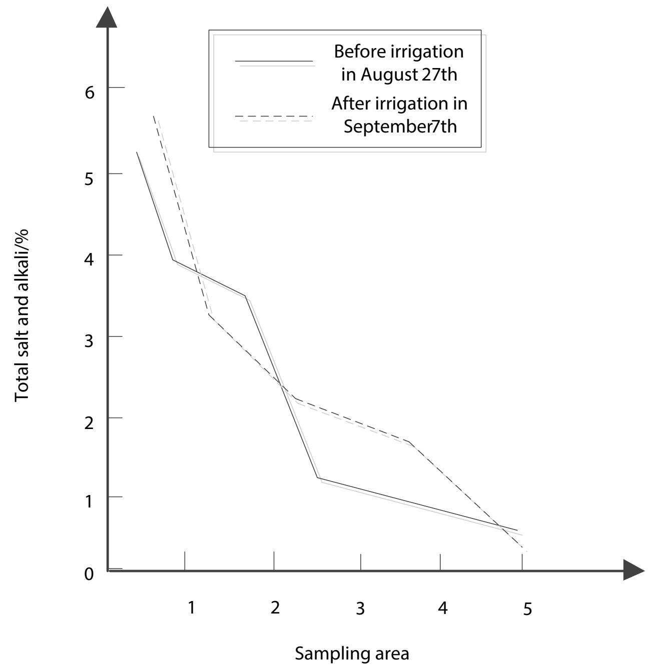


Fig. 5. Distribution of total salt and alkali before and after irrigation in August 27th and September 7th.

The analysis Table 8 shows that due to sub-soiling, between 0 and 50 cm below the soil, the content of saline-alkali changes from small to large, forming a desalination zone of saline-alkali content and increasing a small part of saline-alkali content at 50 cm. The experiment of cotton cultivation with sub-soiling technique on soda saline-alkali soils for 3 years (2011–2013) made the desalination rate of 0–30 cm layer soil reached 83.5%, and that of 0–60 cm layer soil reached 79.9%.

Table 8
Soil salinization under sub-soiling condition

Time	0–30	30–60	60–100	0–60
2010	29.08	23.72	12.22	26.41
2011	13.52	17.62	12.32	15.57
2012	5.04	7.56	9.19	6.29
2013	4.79	5.82	8.75	5.32
Cumulative desalination rate (%)	83.5	75.51	46.12	79.93

Under the same irrigation rate and initial soil water content, the vertical distance of desalination zone decreases with the increase of dripper discharge, which is not conducive to the formation of desalination zone for normal growth of crops. Under the same dripper flow rate, the vertical distance of desalination zone increases with the increase of dripper flow rate, which indicates that sub-soiling technology is beneficial to vertical salt compression. Under the same irrigation rate and dripper discharge, the vertical distance of desalination zone decreases with the increase of initial soil water content.

Because the infiltration capacity of soda saline-alkaline soil is relatively small, the soil cultivated by sub-soiling technology often produces surface water near emitter, so that the horizontal movement rate of soil moisture is greater than the vertical movement rate, and the horizontal movement rate of soil salinity-alkali is greater than the vertical movement rate. The distance of desalting alkali is larger than that of vertical desalting.

3.7. Saline-alkali infiltration of drip irrigation under sub-soiling conditions

After the infiltration of drip irrigation under sub-soiling condition, the wetting body was cut longitudinally with a diameter of the emitter as the origin. The wetting body was measured by TYPE-HH2 soil moisture meter at the horizontal and vertical wetting front on the positive plane of XOY (*X*-axis right positive, *Y*-axis vertical positive) with the emitter as the center. The salinity should be replaced by electrical conductivity [26]. Soil salinity and alkali migrate along the radial direction with the radial migration of water, so during the process of point source drip irrigation infiltration, the salinity and alkali accumulate near the wetting front, and the soil near the emitter is gradually in the process of desalinization. For saline-alkali soil, drip irrigation also meets the requirement of desalt and alkali [27]. Therefore, irrigation not only completes the task of soil water supply but also keeps the salinity of soil in root layer below the salinity tolerance of crops. The three-dimensional change of water content in drip irrigation leads to the corresponding three-dimensional movement of saline-alkali. In this way, the movement of saline-alkali has its specific law [28].

Fig. 6 is a contour map of electrical conductivity of 1/4 section of wetting body after 0 h of drip irrigation center

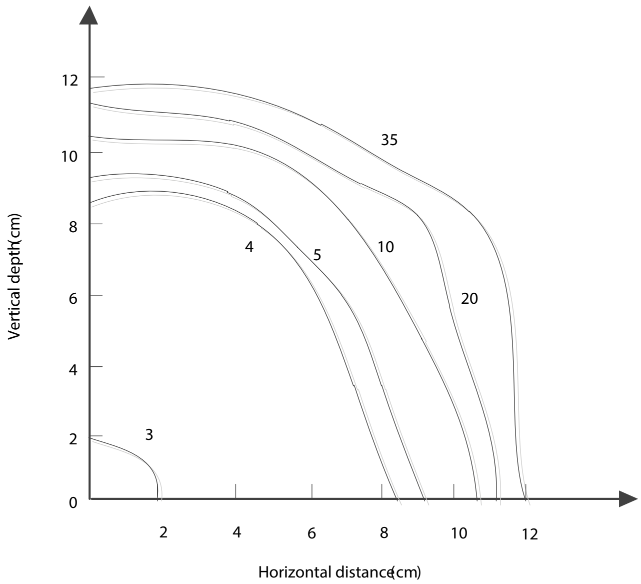
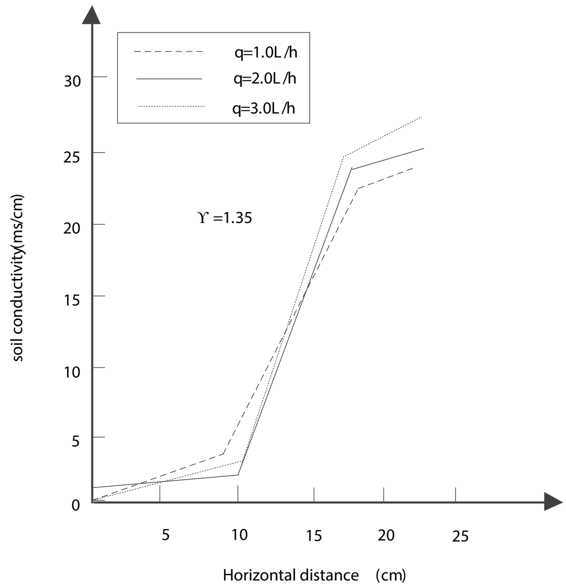
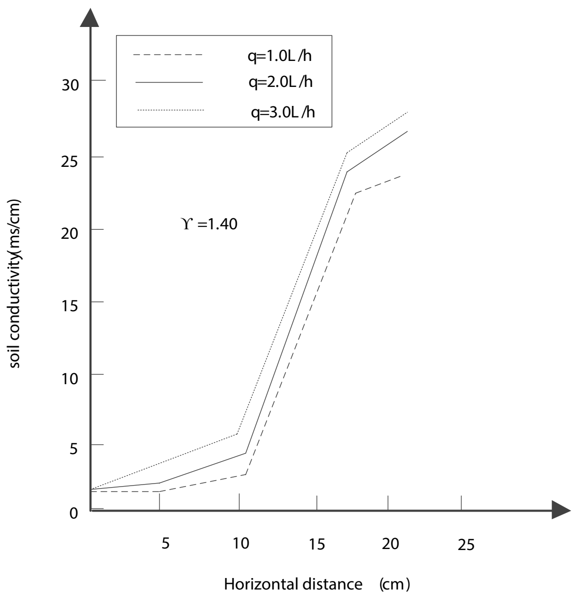


Fig. 6. Contour map of electrical conductivity.



(a) Horizontal conductivity distributions (ϒ=1.35)



(b) Horizontal conductivity distributions (ϒ=1.4)

Fig. 7. Horizontal conductivity distributions.

after infiltration, the unit is ms cm^{-1}. It can be seen that the saline-alkali content of the soil near the emitter is obviously lower than the initial saline-alkali content after water infiltration and leaching. The farther away from the emitter, the saline-alkali content increases faster until the conductivity reaches the maximum at the wetting front. There are obvious salting out areas and saline-alkali areas, and the shape of the salt and alkali area is similar to that of the ellipsoid.

Under certain water content, there is a linear relationship between soil bulk conductivity and soil solution conductivity, so the soil bulk conductivity can be directly used to determine the content and migration of salt and alkali. The variation trend of horizontal wetting radius and vertical stratification (5 cm) of drip irrigation center (0 point) at the end of infiltration under the condition of sub-soiling is shown in Figs. 7 and 8.

It can be seen from Fig. 7 that the soil conductivity of each infiltration velocity (1.0, 2.0, and 3.0 L h^{-1}) is lower than 5 ms cm^{-1} when the horizontal distance is 10 cm, the infiltration velocity (1.0, 2.0, and 3.0 L h^{-1}) is lower than 5.5 ms cm^{-1} when the horizontal distance is 10 cm, and the horizontal distance is 1.40. This indicates that the salinity of the horizontal distance is relatively low.

As can be seen from the Fig. 8, when the average ratio of vertical penetration depth γ is 1.35, when the vertical depth is 4 cm, the soil conductivity of each infiltration velocity (1.0, 2.0, and 3.0 L h^{-1}) is lower than 5 ms cm^{-1}, when the average ratio of vertical penetration depth γ is 1.4, and when the vertical depth is 4 cm, the soil conductivity of each infiltration velocity (1.0, 2.0, and 3.0 L h^{-1}) is lower than 6 ms cm^{-1}. It shows that the vertical salinity is low.

As can be seen from Figs. 7 and 8, both horizontal and vertical salinity decreases with increasing distance from the point source, and most of the wetting bodies are in a desalination state. In the process of drip irrigation, under the soil surface, salinity and alkali gradually diffuse away from the point source with the water, and finally accumulate at the edge of the wet soil. The soil salinity is the lowest in the vicinity of emitter, and the salinity increases with the distance from the emitter. The contour distribution of soil salinity and alkali is similar to that of soil moisture, but it is not as regular as that of wetting front. The variation of salt-alkali content in surface soil is the greatest in the process of infiltration, and the influence of infiltration boundary conditions is the most obvious. The vertical wetting radius under the emitter is the largest, and the vertical distribution of salt-alkali is the most prominent. After 4 L infiltration, the horizontal and vertical desalination and alkali removal at different infiltration velocities (1.0, 2.0, and 3.0 L h^{-1}) are shown in Table 9.

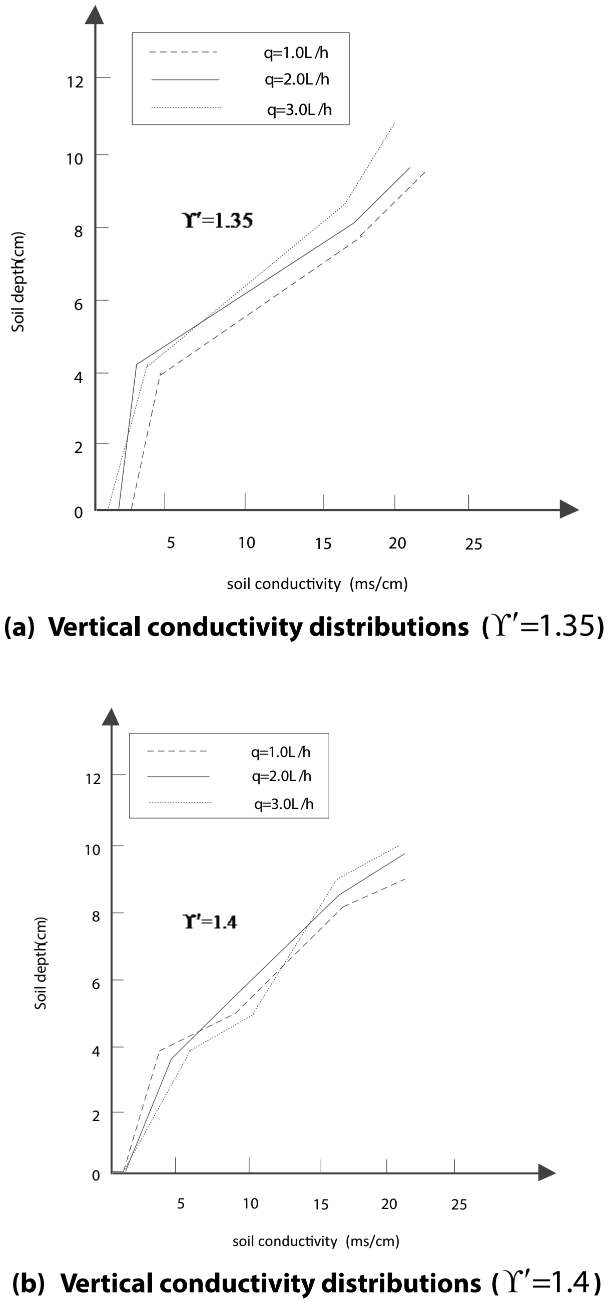


Fig. 8. Vertical conductivity distributions.

Contrasting with Table 9, Figs. 7 and 8, it can be seen that in the infiltration process under sub-soiling conditions, the salinity and alkali diffuse gradually along the direction of water away from the point source, and finally accumulate at the edge of the wet soil. After irrigation, the soil salinity and salinity in each horizontal direction were less than 1.634% of the initial value. Soil salinity and alkali content were lower in the treatment with smaller dripper discharge and lower in the treatment with larger dripper discharge than in the treatment with larger dripper discharge. There was a negative correlation between soil salinity and emitter discharge. This is because saline and alkali in soils exist in soil solutions, colloidal particles and soils by dissolution, adsorption and solids, respectively [29]. If the soil moisture content is relatively low, it exists as a soluble form in the soil, and the saline-alkali in the soil mainly exists in small capillaries. The saline-alkali adsorbed on the colloidal particles in the form of adsorption is surrounded by smaller capillaries. If there is solid saline, the same proportion is mostly found in fine capillary tubes. Therefore, only when the infiltration water moves in the fine capillary can the salt and alkali move down at higher efficiency. According to the capillary management theory of soil moisture and solute transport, when the dripper discharge is large, that is, when the water supply intensity is large, the water moves in the soil capillary under the action of gravity, and the water in the small capillary is relatively immobile, at this time the salt and alkali in the small capillary cannot be leached [30]. Therefore, the efficiency of leaching water is relatively low. Far away from the emitter, the reason why the soil salinity and alkali content in the treatment with large emitter discharge is smaller is that the area of accumulated water is larger and the surface soil salinity and alkali are more sufficient.

With the increase of dripper discharge, the depth of saline-alkali accumulation decreases in turn, which is due to the lower efficiency of treating leaching water with larger dripper discharge. On the other hand, the larger the surface water area formed by the larger dripper discharge, the faster the increase of soil water content in horizontal direction, the weaker the vertical hydraulic conductivity, and the lower the vertical hydraulic conductivity. The vertical washing effect of irrigation water is low.

Table 9 shows that the average ratio of horizontal desalination radius to horizontal wetting radius was 0.863 at 1.35 g cm^{-3} and 0.853 at 1.40 g cm^{-3}. The average ratio of vertical desalination depth to vertical infiltration depth was 0.655 at 1.35 g cm^{-3} and 0.658 at 1.40 g cm^{-3}. It can be concluded that the horizontal desalination is faster than the vertical desalination under sub-soiling condition.

4. Discussion

Sub-soiling technology is the basic technology to improve soda saline-alkali soils. Understanding the saline-alkali transport law of soda saline-alkali soils based on sub-soiling technology is the basis of studying the crop cultivation in saline-alkali soils [31,32].

- The variation laws of surface wetting radius and horizontal wetting radius are similar, showing a power function relationship.
- Under the condition of sub-soiling, the wetting body formed by point source infiltration under drip irrigation is a semi ellipsoid. The larger the dripper discharge, the flatter the ellipsoid; with the increase of irrigation time, the wetting body is close to the hemisphere, and the distribution of salt and alkali is consistent with the distribution of wetting body [33].
- Under the condition of sub-soiling, the horizontal salinity of wetting body increases with the increase of dripper flow rate, while the longitudinal salinity decreases with the increase of dripper flow rate. With the increase of

Table 9
Depth table for drip irrigation infiltration and dehydration under sub-soiling condition

Capacity (g cm^{-3})	1.35	–	–	1.45	–	–
Drip irrigation flow (L h^{-1})	1.0	2.0	3.0	1.0	2.0	3.0
Horizontal wetting radius *R* (cm)	1.71	17.8	18.1	17.2	17.8	18.0
Vertical infiltration depth *H* (cm)	19.0	16.8	15.2	19.2	16.4	15.0
Horizontal desalt alkali radius *r* (cm)	14.8	15.2	15.3	15.2	15.3	15.2
Vertical dehydration depth *h* (cm)	10.8	11.1	11.2	11.3	10.8	10.9
r/*R*	0.865	0.848	0.845	0.884	0.860	0.844
h/*H*	0.568	0.661	0.737	0.589	0.659	0.727

irrigation duration, both horizontal and vertical salinity increased, while both horizontal and vertical salinity decreased with the increase of distance from emitter [34]. However, the vertical axial salinity decreased faster than the horizontal salinity, and the farther away from the emitter, the greater the difference in salinity and alkali content; under different irrigation rates, the horizontal and vertical salinity and wetting velocity of soil wetting body gradually decreased with the increase of time, and the horizontal salinity-alkali wetting velocity was greater than the vertical salinity-alkali wetting velocity at the beginning [35–38]. With the increase of time, the vertical and horizontal wetting rates of salinity and alkali gradually approached; with the same irrigation amount at different dripper discharge, the horizontal diffusion radius and vertical infiltration depth of salinity and alkali increased with the increase of discharge, but the horizontal wetting front of salinity and alkali increased faster.

- Soil salinity was lower in the area with lower dripper discharge and lower in the area with larger dripper discharge. There was a negative correlation between soil salinity and emitter discharge under the emitter. With the increase of emitter discharge, the depth of salt accumulation decreases. The surface soil salinity decreased with the increase of irrigation duration. The saline-alkali content of sub-soiled soil under emitter decreases with the increase of infiltration water, the leaching efficiency and salt-pressure depth of sub-soiled soil by infiltration water are in direct proportion to the irrigation duration.

5. Conclusions

Omni-directional sub-soiling is a fundamental measure to improve the productivity of soda saline-alkali soils. It is suitable not only for general or high-yielding saline-alkali soils but also for the improvement of medium and low-yielding soda saline-alkali soils. The application of sub-soiling technology in soda saline-alkali soils can break the plough bottom, deepen the tillage layer, and enhance the capacity of water storage and moisture conservation. Therefore, in irrigation, because the water source is sufficient, the soil can hold more water. If the organism is short of water during the growing period, the water in the lower soil will also increase to supply the crops for growth, and will not cause grain yield reduction. The sub-soiling technique is suitable for the application in the cultivated land with thicker soil layer, but not in the thin soil layer or sandy soil. The use of sub-soiling technology benefits 3 years at a time, and then it is implemented after 3 years, so that the cycle is 3 years. Application time of sub-soiling technology: soda saline-alkali soils should be selected before the rainy season in July and August after harvest, and autumn crops should be timely sub-soiled after harvest in order to receive rain or winter irrigation in late September and October. It is not suitable to choose dry spring operations.

The law of saline-alkali migration in soda saline-alkali soil based on sub-soiling technology is studied in this paper.

- During the vertical saline-alkali movement under the condition of sub-soiling, with the increase of infiltration head, the depth of desalination zone, the position of saline-alkali content frontal value and the position of saline concentration frontal value also increase. These relations can be used to approximate estimate the depth of desalination zone, the position of salt-alkali content frontal value and the position of salt-alkali concentration frontal value according to the depth of wetting front, so as to guide production practice.
- The characteristics of saline-alkali transport in soda saline-alkali soils can reflect the general variation of soil salinity and alkali. The results show that the saline-alkali concentration increases with the increase of soil depth and the position of saline-alkali concentration front increases with the increase of infiltration duration.
- For the same wetting depth, the depth of desalination zone, the position of saline-alkali content front and the position of saline-alkali ion front deepened with the increase of accumulated infiltration, mainly because the saline-alkali and ions carried away by water increased with the increase of accumulated infiltration. For the same wetting depth, with the increase of cumulative infiltration, the depth and frontal value of salinity change little.
- The dripper discharge and irrigation amount also have great influence on the saline-alkali distribution in drip irrigation point source under sub-soiling condition. The contour distribution of soil salinity and alkalinity is similar to that of soil water content; under the same irrigation quota, with the increase of dripper discharge, the horizontal distance changes little and the vertical distance decreases; under the same dripper discharge and

irrigation amount, with the increase of bulk density of sub-soiled soil, the horizontal distance decreases. The horizontal distance of saline-alkali soils increases little while vertical distance decreases. Under the same dripper discharge and the same soil bulk density, the horizontal and vertical distances in the desalination zone increased with the increase of irrigation amount, which indicated that the increase of sub-soiled soil irrigation amount was beneficial to the formation of desalination zone for normal growth of crops and vertical salt pressure.

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