Effect of Salt Crust Thickness on Soil Water and Salt Distribution Characteristics (Postprint)

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Abstract

Soil salt crusts have significant impacts on soil evolution and eco-hydrological processes in arid regions. Current research on water-salt distribution characteristics of salt-crusted soils is limited and has not considered the influence of salt crust thickness, leading to substantial discrepancies in research findings. Therefore, through laboratory simulation experiments, four initial salt concentrations ($0\ \mathrm{g \cdot L^{-1}}$, $10\ \mathrm{g \cdot L^{-1}}$, $150\ \mathrm{g \cdot L^{-1}}$, and $250\ \mathrm{g \cdot L^{-1}}$) were established to obtain different salt crust thicknesses (4.5 mm, 6.6 mm, and 7.3 mm), and a partial-replication stepwise-removal method was employed to conduct comparative analysis of the dynamic changes in water and salt within the soil profile. The results indicate: (1) Compared with the salt-free treatment, thicker salt crusts in the salt treatments resulted in greater water content in the soil profile and smaller amplitude of change in salt content. (2) At the end of the experiment, the water content distribution characteristics of the 4.5 mm-thick salt crust soil were similar to those of the salt-free treatment, while the water content in the soil profiles with 6.6 mm and 7.3 mm-thick salt crusts was significantly greater than that of the salt-free treatment ($P<0.05$). (3) At the end of the experiment, the minimum salt content in the soil profiles with 4.5 mm, 6.6 mm, and 7.3 mm-thick salt crusts decreased by 90.5%, 46.3%, and 32.1%, respectively, compared with the initial salt content. The research findings verify that salt crust thickness exerts a substantial influence on soil water-salt distribution; therefore, it is recommended that future research on water-salt distribution characteristics of salt-crusted soils should comprehensively consider the effects of salt crust thickness.

Full Text

Effect of Salt Crust Thickness on Distribution Characteristics of Soil Water and Salt

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Abstract

Soil salt crust represents an extreme manifestation of soil salinization and exerts significant influence on soil properties and surface hydrological processes in arid regions. The movement of water and salt in arid zone soils constitutes a complex dynamic process, and the distribution characteristics of soil water and salt affect soil physicochemical and biological processes, thereby influencing heavy metal redistribution and carbon emissions. Salt crusts are ubiquitous in arid regions, making the study of water-salt distribution characteristics in salt-crusted soils theoretically important.

Current research on soil water-salt distribution primarily focuses on non-salt-crusted soils. Studies have shown that when soil surfaces are covered with different materials, evaporation is significantly reduced and surface salt accumulation is mitigated. Salt crusts affect soils similarly to straw mulching, thus inevitably influencing soil water-salt distribution characteristics. However, due to measurement limitations in high-salinity regions and the complexity of coupled water-salt-thermal interactions under salt crust influence, few scholars have investigated water-salt distribution in salt-crusted soils. Some studies have found that salt crusts affect water content variation curves differently across soil textures, with salt accumulating in the 0–4 cm layer and concentrations increasing toward the surface. Other research indicates that salt-crusted soils maintain higher water contents than non-crusted soils, with different crust thicknesses affecting moisture migration patterns and resulting in varying water content across soil layers.

In arid and semi-arid regions, soil salinization exhibits high spatial variability, with salt crusts of various thicknesses widely distributed. Salt concentration is a crucial factor affecting salt crust formation and development. Evaporation represents the primary driver of soil water-salt movement, and different salt crust thicknesses significantly affect soil evaporation rates. Therefore, salt crust thickness must influence soil water-salt distribution characteristics, though the underlying mechanisms remain unclear. This study established four different initial salt concentrations to obtain varying salt crust thicknesses, analyzed the dynamic changes in soil water and salt, identified differences in water-salt distribution characteristics among different crust thicknesses, and elucidated the influence mechanisms of crust thickness on water-salt distribution to provide a theoretical foundation for quantitatively describing surface hydrological processes in saline soils of arid regions.

Keywords: salt crust thickness; water-salt distribution characteristics; evaporation front; HYDRUS-1D model

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1 Materials and Methods

1.1 Experimental Materials The test soil was sandy with a bulk density of 1.65 $\mathrm{g\cdot cm^{-3}}$ and saturated water content of 39.67%. Polyvinyl chloride (PVC) tubes (10 cm diameter × 33 cm height) served as containers, wrapped with thermal insulation material. The sand was washed to remove impurities, with electrical conductivity controlled below 100 $\mathrm{S\cdot cm^{-1}}$, then oven-dried and passed through a 2 mm sieve before uniform packing. A 5 cm layer of filter stone (0.5-1 mm diameter) was placed at the bottom of each tube. Soil columns were fully saturated from bottom to top.

1.2 Experimental Design and Methods Four treatments were established: 0 $\mathrm{g\cdot L^{-1}}$ (non-salt control), 10 $\mathrm{g\cdot L^{-1}}$, 150 $\mathrm{g\cdot L^{-1}}$, and 250 $\mathrm{g\cdot L^{-1}}$ initial salt concentrations to obtain different salt crust thicknesses. The control treatment was saturated with distilled water, while other treatments were saturated with different concentration solutions. Evaporation was measured using an automatic weighing platform (Beijing Shiyu Tong Technology Co., Ltd.) connected to a data logger (Beijing Shiyu Tong Technology Co., Ltd.). A partial repeated stepwise withdrawal method was employed, where selected soil columns were sectioned at specific time points, salt crusts were 剥离 d from the surface, and soil samples were collected at 2 cm intervals above 10 cm depth and at 10 cm intervals from 10–30 cm depth for water content and salt content determination.

Based on previous research on evaporation stages at different initial concentrations, three key nodes were selected as withdrawal times: characteristic time 1 for stage 1, characteristic time 2 for stage 2, and characteristic time 3 for stage 3. Evaporation rates at these times are shown in [Figure 1: see original paper]. Soil water content was determined by oven-drying, and soil salt content was measured by grinding dried samples, passing through a 1 mm sieve, mixing at a 1:5 soil-water ratio, stirring, settling, and measuring electrical conductivity with a conductivity meter. The relationship between salt content and electrical conductivity was calculated as: St = 4.533 × EC - 0.723, where St is soil salt content ($\mathrm{g\cdot kg^{-1}}$) and EC is soil extract electrical conductivity ($\mathrm{mS\cdot cm^{-1}}$). Salt crust thickness was measured with vernier calipers, then crusts were dissolved in distilled water, filtered, and oven-dried for salt mass measurement.

1.3 Soil Water-Salt Dynamic Model The HYDRUS-1D model was used to simulate soil water movement:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]$$

where is volumetric water content ($\mathrm{cm^3 \cdot cm^{-3}}$), t is time (d), z is vertical coordinate (cm), h is pressure head (cm), and K is unsaturated hydraulic conductivity ($\mathrm{cm \cdot d^{-1}}$).

The solute transport equation:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - \frac{\partial(qC)}{\partial z}$$

where C is solute concentration ($\mathrm{g \cdot cm^{-3}}$), D is dispersion coefficient ($\mathrm{cm^2 \cdot d^{-1}}$), and q is water flux ($\mathrm{cm \cdot d^{-1}}$).

Soil hydraulic parameters were obtained from measured water characteristic curves using HYPROP software, while solute transport parameters were determined based on literature and refined using HYDRUS-1D with measured water and salt contents. Final hydraulic and solute transport parameters for different treatments are shown in . The model height was 30 cm with 61 nodes at 0.5 cm spacing, with observation points at 10 cm, 20 cm, and 25 cm depths. Simulation time matched experimental duration, then extended to 120 d to observe evaporation front movement.

1.4 Model Initial and Boundary Conditions For water movement, initial condition was saturated water content, upper boundary was variable flux (using measured evaporation flux), and lower boundary was zero flux. For solute transport, initial condition was initial saturated concentration, with concentration flux boundaries at both top and bottom.

1.5 Data Processing Data were analyzed using SPSS 25 and graphed with Origin 2018 and Excel 2019. Model validation used coefficient of determination ($\mathrm{R^2}$) and root mean square error (RMSE). Higher $\mathrm{R^2}$ and lower RMSE indicate better simulation accuracy. RMSE is calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - M_i)^2}$$

where N is sample size, S is simulated value, and M is measured value.

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2 Results and Analysis

2.1 Dynamic Changes in Soil Water Content Under Different Salt Crust Thicknesses Salt crusts at the end of the experiment are shown in [Figure 2: see original paper]. Salt crust mass and thickness varied among treatments and over time ([Figure 3: see original paper]), with mass increasing and thickness growing over time. Soil salt content significantly affected crust thickness. Previous research showed crust thickness increased with salt concentration from 0.5 to 2.5 $\mathrm{mol \cdot L^{-1}}$, consistent with our findings. At the end of the experiment, crust thicknesses were 4.5 mm, 6.6 mm, and 7.3 mm for the 10 $\mathrm{g \cdot L^{-1}}$, 150 $\mathrm{g \cdot L^{-1}}$, and 250 $\mathrm{g \cdot L^{-1}}$ treatments, respectively.

Water content distribution characteristics in the 4.5 mm crust treatment were similar to the non-salt control. The 6.6 mm and 7.3 mm crust treatments showed significantly higher water contents than the control ($P<0.05$). Thicker salt crusts resulted in greater soil water content because salt solutions altered soil osmotic potential and reduced saturated vapor pressure, inhibiting upward water transmission.

For the surface layer (0-2 cm), water contents were 0.202, 0.293, and 0.329 $\mathrm{cm^3 \cdot cm^{-3}}$ for the 4.5 mm, 6.6 mm, and 7.3 mm treatments at characteristic time 1, significantly higher than the control (0.019 $\mathrm{cm^3 \cdot cm^{-3}}$). At characteristic time 2, surface water content decreased to 0.009 $\mathrm{cm^3 \cdot cm^{-3}}$ in the control (essentially dry), while salt treatments maintained 0.050-0.194 $\mathrm{cm^3 \cdot cm^{-3}}$ due to crust inhibition of water loss. By the end of the experiment, surface water contents in salt treatments remained above 0.008 $\mathrm{cm^3 \cdot cm^{-3}}$, with thicker crusts maintaining higher moisture.

In the upper layer (2-10 cm), water content changes were substantial. At characteristic time 1, upper layer moisture began migrating upward due to surface drying, with the control showing smaller changes due to lower evaporation driving force. At characteristic time 2, a sudden increase in water content at 2-4 cm depth indicated evaporation front movement. The 4.5 mm treatment showed this moisture jump at 2-4 cm, while 6.6 mm and 7.3 mm treatments showed no clear front descent, likely because high salt ion concentrations affected water movement states and rapid crust formation hindered water transmission. By experiment end, upper layer water contents followed the order: 7.3 mm > 6.6 mm > 4.5 mm > control, with thicker crusts maintaining higher moisture.

In the lower layer (10-30 cm), water content increased with depth and changed more gradually. Thicker crusts resulted in greater lower-layer water content because crust growth reduced evaporation driving force, slowing upward moisture migration. At experiment end, lower layer water content in the 4.5 mm treatment was significantly lower than the control ($P<0.05$), possibly because thin crusts had minimal inhibitory effect and crust formation increased evaporation exchange area, enhancing evaporation rates. For 6.6 mm and 7.3 mm treatments, this special effect did not significantly impact crust inhibition, resulting in lower layer water contents much higher than the control.

2.2 Dynamic Changes in Soil Salt Content Under Different Salt Crust Thicknesses

Salt content variations at different depths over time are shown in [Figure 5: see original paper]. In the surface layer, all salt treatments accumulated salt at the surface due to evaporation-driven upward migration and subsequent crystallization when concentrations reached saturation. At characteristic time 1, surface salt content was lower than initial values in the 150 $g \cdot L^{-1}$ and 250 $g \cdot L^{-1}$ treatments (3.28 and 29.54 $g \cdot kg^{-1}$, respectively) but higher in the 10 $g \cdot L^{-1}$ treatment (45.79 $g \cdot kg^{-1}$), likely because lower initial concentrations required more upward migration to reach saturation.

As the experiment progressed, surface salt content decreased then stabilized. By experiment end, surface salt contents were 15.87, 31.08, and 64.00 $g \cdot kg^{-1}$ for the 4.5 mm, 6.6 mm, and 7.3 mm treatments, respectively, all lower than initial values. The minimum salt content in the profile occurred in the upper layer (2-10 cm). At characteristic time 1, minimum salt content was at 2–6 cm depth; by characteristic time 2, it stabilized at 2–4 cm. The minimum salt contents at experiment end were 0.31, 7.26, and 33.20 $g \cdot kg^{-1}$ for the three treatments, representing decreases of 90.5%, 46.3%, and 32.1% from initial values, respectively. Thicker crusts showed smaller salt content reduction amplitudes.

In the lower layer (10–30 cm), salt content increased with depth, and thicker crusts resulted in smaller reduction amplitudes. The 4.5 mm treatment showed significantly different salt distribution from the control, with salt peaks in the lower layer rather than the surface. This occurred because low initial concentration required continuous upward salt supply, slow crust formation, and weak inhibition, allowing sustained salt migration. In contrast, the 250 $g \cdot L^{-1}$ treatment with high initial concentration rapidly formed thick crusts that inhibited water-salt transmission, resulting in minimal lower-layer salt content changes.

Salt balance analysis showed that higher initial concentrations produced greater salt output mass. At experiment end, output salt masses were 2.13, 24.36, and 33.04 g for the three treatments, accounting for 67.3%, 32.1%, and 15.9% of total salt mass, respectively. Higher initial concentrations had lower evaporation rates, reducing upward salt migration velocity.

2.3 Simulation of Soil Profile Water-Salt Dynamic Changes The HYDRUS-1D model simulated water content changes over time ([Figure 6: see original paper]). Simulation accuracy was highest at characteristic time 1 (R^2 = 0.93-0.98, RMSE = 0.004-0.006 $cm^3 \cdot cm^{-3}$) and lowest at experiment end (R^2 = 0.85-0.93, RMSE = 0.006-0.008 $cm^3 \cdot cm^{-3}$). Model accuracy improved over time. Initial concentration significantly affected parameters α and n, with α decreasing and n increasing as initial concentration increased. According to the soil air entry value formula, higher initial concentrations resulted in larger air entry values, making water more difficult to extract and causing smaller water content changes, which may explain poorer simulation accuracy in early stages.

Due to experimental limitations, evaporation front movement below 0.1 cm depth could not be fully observed. The model extended evaporation time to 120 d to monitor water content dynamics. Results showed that for the 4.5 mm treatment, water content 突变 occurred at 0.1 cm depth at 100 d, indicating the evaporation front at that depth, which continued descending to 15 cm by 120

d. For the 6.6 mm treatment, the front descended to 10 cm by 120 d, while for the 7.3 mm treatment, it remained near the surface. This demonstrates that thicker salt crusts significantly slow surface drying and greatly prolong evaporation front descent time.

The HYDRUS-1D solute module could not adequately reflect salt migration after crust formation, so a piecewise simulation approach was adopted. The experiment was divided into three stages: stage 1 (crust formation), stage 2 (crust growth), and stage 3 (crust stabilization). Simulated salt contents are shown in [Figure 7: see original paper]. Stages 1 and 3 showed good simulation accuracy ($R^2 > 0.85$), while stage 2 was relatively poor. Dispersion coefficient (D) increased with initial salt concentration due to different solution flow velocities. D values were smaller in stage 3 than stage 2, possibly because crust formation altered soil porosity.

Detailed analysis of evaporation front zones revealed that water content 突变 occurred across a narrow 1–2 cm zone for all salt treatments, validating the narrow evaporation front concept rather than the wide transition zone proposed by some scholars.

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3 Conclusions

This study analyzed the effects of different salt crust thicknesses on soil water-salt distribution characteristics through laboratory simulation experiments and HYDRUS-1D modeling. The results confirm that salt crust thickness significantly influences soil water-salt distribution.

1. Compared with the non-salt treatment, thicker salt crusts resulted in greater soil profile water content. At experiment end, the water content distribution in 4.5 mm crust soil was similar to the control, while 6.6 mm and 7.3 mm crust soils showed significantly higher water contents ($P<0.05$).
2. As salt crust thickness increased, the amplitude of soil salt content change decreased. At experiment end, the minimum salt contents in 4.5 mm, 6.6 mm, and 7.3 mm crust soils decreased by 90.5%, 46.3%, and 32.1% from initial values, respectively.
3. Combined experimental and modeling analysis revealed that thicker salt crusts require longer time for evaporation front descent. This study verifies that salt crust thickness substantially affects soil water-salt distribution characteristics, suggesting that future quantitative analyses of water-salt distribution in salt-crusted soils should comprehensively consider crust thickness effects.

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