Soil Salinity Accumulation Characteristics During Non-irrigation Season in Long-term Drip-irrigated Cotton Fields (Postprint)

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Abstract

The movement and variation characteristics of soil water and salt during freeze-thaw processes in the non-irrigation season directly affect spring crop irrigation decisions. This study conducted field sampling and monitoring of six cotton field plots with different drip irrigation years in the Xinjiang oasis irrigation district to investigate the laws of soil water and salt transport during freeze-thaw processes and the characteristics of soil salt accumulation in cotton fields with different drip irrigation years. The results showed that: (1) With the increase of drip irrigation years, the salt distribution characteristics in cotton fields changed from surface accumulation to deep-layer accumulation. (2) During the freeze-thaw process, there were significant plot differences in the characteristics of soil salt movement in cotton fields; the wasteland (CK) and plots with 17 a, 19 a, and 23 a of drip irrigation showed a salt-return trend, with average salt fluxes of 43.61 g · m-2 · d-1, 172.57 g · m-2 · d-1, 38.18 g · m-2 · d-1, and 10.53 g · m-2 · d-1, respectively. (3) The ablation period was the most active period for water and salt transport in the wasteland (CK) and plots with 13 a, 15 a, 17 a, 19 a, and 23 a of drip irrigation; after freeze-thaw, the soil water storage in the sensitive zone (0~60 cm) of all plots increased by 23.43mm, 81.26 mm, 31.68 mm, 62.39 mm, 96.98 and 69.64 mm, respectively. This study reveals the laws of soil water and salt transport during freeze-thaw processes and the characteristics of salt accumulation in cotton fields with different drip irrigation years, which can provide scientific guidance for soil management under freeze-thaw conditions during the non-irrigation season and under long-term drip irrigation in Xinjiang.

Full Text

Soil Salt Accumulation Characteristics of Long-term Drip Irrigation in Cotton Fields During Non-irrigation Seasons

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Abstract

The movement and transformation characteristics of soil water and salt during the freezing-thawing process in non-irrigation seasons directly affect spring crop irrigation decisions. This study conducted field sampling and monitoring on cotton fields with different drip irrigation years in the Xinjiang oasis irrigation area to explore the laws of soil water-salt transport during freezing-thawing and the salt accumulation characteristics in cotton fields under different drip irrigation durations. The results showed that: (1) During the freezing-thawing process, significant plot differences existed in soil salt movement characteristics in cotton fields. The wasteland (CK) plot exhibited a salt return trend, with an average salt flux of 172.57 $g \cdot m^{-2} \cdot d^{-1}$. (2) With increasing drip irrigation years, the salt distribution pattern in cotton fields shifted from surface accumulation to deep-layer accumulation. (3) The ablation period was the most active period for water and salt transport in both wasteland and cotton field plots. After freezing-thawing, the sensitive zone (0–60 cm) of all plots showed increased soil water storage, with increments of 23.43 mm, 81.26 mm, 31.68 mm, 62.39 mm, 96.98 mm, and 69.64 mm for the wasteland and cotton fields with 13, 15, 17, 19, and 23 drip irrigation years, respectively. This study reveals the laws of soil water-salt transport during the freezing-thawing process and the salt accumulation characteristics in cotton fields under long-term drip irrigation, providing scientific guidance for soil management in Xinjiang under non-irrigation season freeze-thaw conditions and long-term drip irrigation.

Keywords: drip irrigation cotton field; freeze-thaw; salt flux; salt accumulation; water loss

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Introduction

Compared with traditional irrigation methods, mulched drip irrigation technology has been widely adopted in arid and semi-arid regions due to its excellent water-saving and moisture-preserving performance. As the most typical demonstration area for mulched drip irrigation technology in China, Xinjiang' s mulched drip irrigation area has exceeded 1.28×10^{6} hm^2. However, during the large-scale promotion and application of mulched drip irrigation technology in Xinjiang, most drainage ditches have been filled, causing soil salts to lose their pathway for removal and merely redistribute within the soil profile, with salts continuing to accumulate in the soil body. A salt 淡化层 (desalination layer) forms in the tillage layer, creating a "desalination illusion" that ensures normal crop growth and development in the short term, but soil surface salt content remains high after spring. The contradiction between desalination and salt accumulation in long-term mulched drip irrigation cotton fields persists.

Soil salt content directly affects cotton growth, but the application of mulched drip irrigation technology significantly reduces shallow soil salt content, thereby potentially improving cotton emergence rate and yield. Therefore, investigating the impact of seasonal freezing-thawing on soil salt spatiotemporal changes in cotton fields with different drip irrigation years is crucial for scientifically guiding spring irrigation decisions and ensuring the sustainable development of mulched drip irrigation technology.

In countries and regions with extensive seasonal frozen soils, the movement and distribution patterns of soil water-salt during freezing-thawing have long been research hotspots. Understanding water and salt movement during freezing-thawing is essential for rational land resource development, crop yield improvement, and saline-alkali disaster prevention. Non-irrigation season soil salt movement occurs throughout the entire freezing-thawing process. Due to temporal and spatial variations in ground temperature during freezing, soil undergoes periodic freezing and thawing. During top-down freezing, soil water phase-changes into ice, creating significant soil-water potential gradients above and below the frozen layer that drive salt transport from bottom to top, making surface salt accumulation possible during freezing. However, some scholars argue that during the ablation period, large amounts of snowfall and melting of "frozen layer detained water" can effectively leach surface soil salts, resulting in surface desalination. Conversely, other studies suggest that strong evaporation and snowmelt during spring ablation can raise the groundwater level, intensifying surface salt accumulation, and that freeze-thaw action is a primary driver of soil salinization. Therefore, the spatiotemporal distribution changes of soil water-salt in cotton fields during non-irrigation seasons have non-negligible effects on cotton growth.

This study conducted natural soil sampling observations on five cotton fields with different drip irrigation years to reveal salt migration laws during freezing-thawing and salt accumulation characteristics under different drip irrigation durations, providing a scientific basis for the sustainable application of mulched drip irrigation technology in oasis cotton fields.

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1. Materials and Methods

1.1 Study Area Overview

The experimental site is located at the 121st Regiment of the 8th Division, Xinjiang Production and Construction Corps (85°32 47 -85°34 15 E, 44°45 85 -44°48 48 N). The region has a typical temperate continental climate and is a typical seasonal frozen soil area. In 2020, the total annual rainfall was 84.3 mm, with a daily average temperature of 8.37°C, maximum temperature of 38.7°C, and minimum temperature of -27.1°C. During the experimental period (December 2019 to March 2020), total precipitation was 38.5 mm and average temperature was -8.56°C.

This study selected five cotton fields that began using mulched drip irrigation technology in 1997, 1999, 2003, 2005, and 2007 (with 23, 19, 17, 15, and 13 drip irrigation years, respectively), plus a wasteland plot as control (CK). The cotton fields had uniform field management and consistent irrigation systems. Before freezing, all cotton fields received the same winter irrigation quota of 2250 $m^3 \cdot hm^{-2}$.

1.2 Sample Collection and Measurements

1.2.1 Soil Moisture and Salt Content Soil samples were collected during three freezing-thawing stages: pre-freezing (December 15, 2019), freezing period (January 23, 2020), and ablation period (March 5, 2020). Soil samples were obtained using an auger. To eliminate horizontal salt differences caused by drip irrigation, three sampling zones were established in each cotton field, with three sampling points at 50 cm horizontal spacing in each zone. Sampling depths were 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-60 cm, 60-70 cm, 70-80 cm, 80-90 cm, 90-100 cm, 100-120 cm, 120-140 cm, 140-160 cm, 160-180 cm, and 180-200 cm. Soil samples from the same depth in each plot were mixed, and the average of the three sampling zones was used as the representative data for each plot.

Soil mass water content was determined using the oven-drying method. After drying, soil samples were ground and passed through a 1 mm sieve. A 1:5 soil-water ratio extract was prepared, shaken for 5 minutes, settled, filtered, and the supernatant was used to measure electrical conductivity (EC) with a DDS-11A conductivity meter. Soil total salt content was calibrated using the residue method, with calibration results shown in Figure 2.

1.2.2 Soil Salt Storage and Salt Flux The salt storage (referred to as salt storage) per unit area (1 m^2) in the h-depth soil layer was calculated using Equation (1):

$$S = \gamma \times C \times h \times \frac{1}{10}$$

where:
- S is the salt storage in the h-depth soil layer ($g \cdot m^{-2}$)
- γ is the dry bulk density of the soil layer ($g \cdot cm^{-3}$)
- C is the soil salt content ($g \cdot kg^{-1}$)
- h is the soil layer depth (cm)

Assuming one-dimensional vertical salt movement in soil, salt flux was calculated using Equation (2):

$$Q_i = \frac{\Delta S_i}{t}$$

where:
- Q_i is the salt flux at the upper and lower interfaces of the target soil layer ($g \cdot m^{-2} \cdot d^{-1}$)
- ΔS_i is the change in salt storage in the i-th soil layer ($g \cdot m^{-2}$)
- t is the duration of the period (d)

By definition, if $Q > 0$, the soil layer accumulated salt during the calculation period; if $Q < 0$, salt content decreased.

1.2.3 Soil Water Storage and Water Loss The water storage in the h-depth soil layer was calculated using Equation (3):

$$W = \gamma \times \theta \times h \times \frac{1}{10}$$

where:
- W is the water storage in the h-depth soil layer (mm)
- θ is the soil mass water content (%)

Water loss was calculated using Equation (4):

$$\Delta W = W_i - W_j$$

where:
- ΔW is the soil water storage loss (mm)
- W_i is the water storage in the previous stage (mm)
- W_j is the current water storage (mm)

When $\Delta W > 0$, it indicates water loss; when $\Delta W < 0$, it indicates water gain.

1.3 Data Analysis

Data were organized and preprocessed using Excel 2010. One-way ANOVA was performed using SPSS 20.0 software, and figures were created using Origin 2020 software.

2. Results

2.1 Soil Salt Distribution Characteristics

2.1.1 Spatiotemporal Distribution of Soil Salt in Cotton Fields with Different Drip Irrigation Years The vertical salt distribution in the wasteland plot during the pre-freezing period showed that wasteland salt storage decreased layer by layer down the profile, with maximum surface soil salt storage (1809.84 $g \cdot m^{-2}$), representing a typical surface-accumulation profile (Figure 3). In drip irrigation cotton fields, salt storage showed an increasing trend with depth, representing a bottom-accumulation profile (Figure 3).

Analysis of total salt storage in each soil layer of cotton fields with different drip irrigation years during the pre-freezing period revealed that total salt storage in the 0–60 cm and 60–120 cm layers decreased significantly with drip irrigation years ($P < 0.05$), with determination coefficients (R^2) of 0.83 and 0.89, respectively. Although total salt storage in the 120–200 cm layer and the entire profile also showed decreasing trends ($R^2 = 0.43$ and 0.44, respectively), the changes were not significant with drip irrigation years (Figure 4).

2.1.2 Evolution Characteristics of Soil Salt in Cotton Fields with Different Drip Irrigation Years With increasing drip irrigation years, the salt distribution pattern in cotton fields shifted from surface-accumulation to uniform distribution. The cotton field with 23 drip irrigation years showed minimal overall fluctuation in soil salt distribution, with significantly lower deep soil salt storage than other plots, indicating that salt distribution had become uniform in the vertical direction (Figure 3). This finding is consistent with Li et al.' s research results on soil salt dynamics under different cultivation periods. However, the leaching effect on soil salt in the 0–120 cm layer was not significant, demonstrating the limitations of drip irrigation in salt leaching. Salts persist in the soil profile, and combined with strong surface evaporation and groundwater dynamics, the probability of soil salinization increases.

2.2 Water-Salt Transport During Freezing-Thawing

2.2.1 Salt Accumulation Characteristics During Freezing-Thawing During the pre-freezing period, salt in all plots moved downward, with the wasteland showing significantly greater movement than drip irrigation plots. The average salt flux was -155.59 $g \cdot m^{-2} \cdot d^{-1}$, decreasing with depth, indicating overall salt leaching and reduced soil salt content during this period. Drip irrigation plots showed less intense salt movement than the wasteland. During this period, except for salt accumulation in the 30–70 cm layer of the 13-year plot and the 120–140 cm layer of the 15-year plot, all other layers in drip irrigation plots showed decreased salt content. Notably, the wasteland 0–20 cm layer had an average salt flux of -59.20 $g \cdot m^{-2} \cdot d^{-1}$, while the 13-year, 15-year, 17-year, and 19-year plots had fluxes of -5.83, -5.08, -0.88, and -0.55 $g \cdot m^{-2} \cdot d^{-1}$, respectively.

During the freezing period, soil salt changes were smaller, with salt flux amplitudes significantly lower than in the pre-freezing period. The wasteland 0–120 cm layer, the 13-year plot 40-180 cm layer, and the 15-year plot 20-200 cm layer continued to show decreased salt content, with average salt fluxes of -53.87 $g \cdot m^{-2} \cdot d^{-1}$. Another pattern showed overall salt increase, with flux amplitude increasing with depth. For example, the wasteland and 23-year plot had average salt fluxes of 43.61 and 172.57 $g \cdot m^{-2} \cdot d^{-1}$, respectively. The remaining layers showed salt accumulation, with the 23-year plot showing overall salt increase and flux increasing with depth, averaging 5.67 $g \cdot m^{-2} \cdot d^{-1}$.

The ablation period was the most active period for soil salt movement in all plots. During this period, salt changes could be divided into two patterns. One pattern showed overall decrease, with flux decreasing with depth, as seen in the 13-year, 15-year, and 17-year plots, with average salt fluxes of -61.46, -53.87, and -2.08 $g \cdot m^{-2} \cdot d^{-1}$, respectively. The other pattern showed overall increase, with flux increasing with depth, as seen in the wasteland, 19-year, and 23-year plots, with average salt fluxes of 38.18, 10.53, and 172.57 $g \cdot m^{-2} \cdot d^{-1}$, respectively, indicating salt return trends.

2.2.2 Water Loss Characteristics During Freezing-Thawing Based on water storage distribution in each plot during the freezing-thawing period, the soil profile could be divided into three zones: the 0–60 cm sensitive zone, the 60–120 cm stable zone, and the 120–200 cm deep active zone. The sensitive zone was most affected by solar radiation, sunshine intensity, temperature, and other environmental factors, where water was easily lost and recovered. This zone was also the main root growth area for cotton, and its dynamic water storage changes directly affected root growth, making it the focus of this analysis. The stable zone showed minimal water storage fluctuations and relatively stable distribution characteristics, being less affected by external factors. The deep active zone' s water storage fluctuations were mainly influenced by groundwater dynamics, showing strong variability.

Analysis of water loss in the sensitive zone of each plot revealed that during the pre-freezing period, the wasteland sensitive zone water storage decreased by 3.89 mm, while other drip irrigation plots increased by an average of 14.82 mm. During the freezing period, the 13-year plot water storage decreased by 45.89 mm, while other plots increased. During the ablation period, all plots showed increased water storage, with an average increase of 20.98 mm. After the complete freeze-thaw cycle, the wasteland and drip irrigation cotton field sensitive zone water storage increased by 23.43 mm and 81.26 mm, 31.68 mm, 62.39 mm, 96.98 mm, and 69.64 mm, respectively, with the ablation period being the main contributor to soil water storage increase.

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3. Discussion

This study found that salt distribution patterns shifted from surface-accumulation to uniform distribution with increasing drip irrigation years. The 23-year plot showed minimal vertical fluctuation in soil salt distribution, with significantly lower deep soil salt storage, indicating uniform vertical salt distribution. This aligns with Li et al.' s research on soil salt dynamics under different cultivation periods. However, the leaching effect on 0–120 cm soil salt was not significant, demonstrating the limitations of drip irrigation in salt leaching. Salts persist in the soil profile, and combined with strong surface evaporation and groundwater dynamics, the risk of soil salinization increases.

Zhang et al. found that 0–60 cm soil salt accumulated with drip irrigation years, which differs from our conclusions. This discrepancy is due to their use of brackish water irrigation (average salt content 2.52 $g \cdot L^{-1}$), where external salt input was the main cause of soil accumulation. Notably, this study collected salt data after cotton harvest, representing a relatively stable salt state after irrigation cessation, allowing more objective comparison of salt changes among plots with different drip irrigation years. Previous studies often collected data during the growing season when salt dynamics were more affected by current irrigation regimes.

Salt flux is a powerful parameter for characterizing salt movement between soil layers and depicting salt accumulation features. Li et al. found that 0–140 cm soil salt storage decreased before and after freezing-thawing, suggesting natural freeze-thaw cycles could leach cotton field salts, but their study lacked analysis of salt movement during the freeze-thaw process. In this study, during the pre-freezing period, 0–120 cm salt moved downward in all plots, with flux decreasing as drip irrigation years increased. This was mainly due to significantly reduced salt content in this layer with drip irrigation years, weakening salt movement intensity. During the freezing period, plot differences emerged: the 13-year plot showed upward salt movement in all layers, while other plots showed alternating positive and negative fluxes in different layers, similar to Peng et al.' s findings. During the ablation period, except for the 13-year plot, all other plots showed overall upward salt movement, indicating salt return trends, consistent with Kang et al. and Zhang et al. The 13-year plot continued to show downward salt movement, 呼应 ing Li et al.' s conclusion about frozen layer detained water leaching salts. This study found that wasteland salt changes were more dramatic than cotton fields during the pre-freezing period, possibly due to long-term mulched drip irrigation altering soil structure, particle arrangement, and pore distribution, changing salt movement pathways and reducing salt movement amplitude during freeze-thaw.

Xinjiang' s arid oasis cotton fields are crucial for economic crops. To inhibit post-thaw salt return affecting cotton growth after spring sowing, this study suggests that under current irrigation regimes, cotton straw mulching could be implemented during non-irrigation seasons to reduce soil water evaporation while suppressing salt return. Additional leaching quotas could be applied, but water resource conservation must be considered.

The ablation period contributed most to water increase in the sensitive zone (Table 1). Although there remains a time interval between monitoring and cotton sowing, during which temperatures will continue rising and precipitation is scarce, soil water will likely be in a state of loss. Since cotton in this region follows a "dry sowing and wet emergence" pattern, water loss during this period will determine the emergence irrigation quota. Previous studies indicate that surface mulching during the annual or freeze-thaw period effectively preserves soil water. Shan et al. noted that mulching during the freeze-thaw period is more practical for water conservation. Therefore, to maintain soil water and conserve water resources, straw mulching of cotton fields during the freeze-thaw period is recommended, which also positively prevents soil frost damage and conserves water.

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4. Conclusions

Based on analysis of soil water and salt changes during freezing-thawing in five cotton fields with different drip irrigation years, the following conclusions were drawn:

1) With increasing drip irrigation years, soil salt storage in the 0–120 cm layer of cotton fields decreased significantly ($P < 0.05$), and salt distribution patterns shifted from surface-accumulation to bottom-accumulation types.

2) During the pre-freezing period, 0–20 cm soil salt in the wasteland moved downward with an average salt flux of -59.20 $g \cdot m^{-2} \cdot d^{-1}$, while the 13-year, 15-year, 17-year, and 19-year plots had average fluxes of -5.83, -5.08, -0.46, and -0.55 $g \cdot m^{-2} \cdot d^{-1}$, respectively. During the freezing and ablation periods, plot differences in salt movement emerged. During freezing, the 13-year plot showed overall salt increase with an average flux of 5.67 $g \cdot m^{-2} \cdot d^{-1}$, while other plots showed alternating positive and negative fluxes in different layers. During ablation, the wasteland and 19-year and 23-year plots showed overall salt increase, indicating salt return trends.

3) The 0–60 cm layer was the sensitive zone for soil water storage in drip irrigation cotton fields. After freezing-thawing, water storage in this zone of the wasteland and the 13, 15, 17, 19, and 23-year plots increased by 23.43 mm, 81.26 mm, 31.68 mm, 62.39 mm, 96.98 mm, and 69.64 mm, respectively, with the ablation period being the main contributor to soil water storage increase.

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Note: Figure translations are in progress. See original paper for figures.