Analysis of Salinity Control and Leaching Effects of Subsurface Pipe Drainage on High Water Table Mulched Drip Irrigation Cotton Fields in Southern Xinjiang (Postprint)

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Abstract

Cotton cultivation with drip irrigation under plastic film is prone to intra-annual soil salt accumulation and continuous inter-annual salt accumulation. Therefore, to explore the response of soil salinity in cotton fields during the entire growth period to different layout parameters of subsurface pipes, subsurface pipe amelioration experiments were conducted in local high-water-table salinized cotton fields under multi-year drip irrigation with plastic film, analyzing the control and leaching effects of the drip irrigation under plastic film - subsurface pipe drainage model on characteristic saline soils in southern Xinjiang. The results show that: when using subsurface pipes for salt control in cotton fields, cotton can grow in a suitable soil salinity environment, and enable salinized cotton fields to transform from intra-annual salt accumulation to desalination by the end of the growth period, while theoretically reducing or exempting water usage for winter and spring irrigation; moreover, the range and threshold values of the soil salt balance point increase with increasing subsurface pipe spacing, and the soil salt control effect decreases accordingly. When no subsurface pipes are laid, soil salt return occurs after irrigation during the growth period; after laying subsurface pipes, irrigation has varying degrees of leaching effect, and the leaching effect decreases with increasing spacing. According to the differences in soil desalination rate and regression analysis, there are significant differences between W1 and W2, W3 ($P<0.1$), and the effect of subsurface pipe spacing on soil desalination rate is more significant than that of burial depth. W1D1 and W1D2 were identified as the better schemes in the experimental design. Since a spacing of 20 m also has good salt discharge and control effects, based on economic considerations, it is recommended to adopt 20 m as a reasonable spacing for non-heavily salinized cotton fields. This study can provide a theoretical basis for saline soil improvement in arid regions and the promotion and application of subsurface pipe drainage technology in southern Xinjiang.

Full Text

Analysis of Salt Control and Leaching Effects of Subsurface Drainage on Mulched Drip-Irrigated Cotton Fields with High Groundwater Levels in Southern Xinjiang

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Abstract

Soil salinization and continuous salt accumulation across years are common problems in cotton production under mulched drip irrigation. To explore how soil salinity during the entire growth period responds to different subsurface pipe layout parameters, we conducted subsurface drainage improvement experiments in long-term mulched drip-irrigated cotton fields with high groundwater levels and salinization levels in Southern Xinjiang. The effects of combined mulched drip irrigation and subsurface drainage on salt management and leaching in this region's characteristic saline soils were analyzed. Results showed that subsurface pipe systems enabled cotton growth in a suitable soil salinity environment and transformed saline cotton fields from net salt accumulation to net desalination by the end of the growth period, while theoretically reducing or eliminating the need for winter-spring irrigation water. The range and threshold values of the soil salt equilibrium point increased with wider pipe spacing, reducing salt control effectiveness. Without subsurface pipes, salt return occurred after irrigation during the growth period, whereas pipe installation produced varying degrees of leaching effects that diminished with increased spacing. Based on differential analysis and regression of soil desalination rates, significant differences were observed ($P < 0.05$), with W1D1 identified as the optimal configuration in our experimental design. Pipe spacing exhibited a more pronounced effect on desalination rate than burial depth. Since the 20 m spacing also demonstrated good salt discharge and control effects, we recommend this as a reasonable spacing for non-heavily salinized cotton fields based on economic considerations. This study provides a theoretical basis for saline soil improvement in arid regions and the promotion of subsurface drainage technology in Southern Xinjiang.

Keywords: subsurface pipes; soil salinization; drip irrigation under mulch; cotton; high groundwater level; desalination; Southern Xinjiang

1 Introduction

Soil salinity is a primary factor limiting crop productivity in arid and semi-arid regions. Irrigated soils are particularly vulnerable to salinization, with approximately 20% of irrigated land worldwide currently affected by salt stress. On dryland agricultural soils, 19.5% are impacted by varying degrees of salinity. As global food production must increase by 70% by 2050 to meet the needs of population growth, salinity represents one of the most severe environmental stresses hindering crop yield improvement.

Xinjiang, located in the arid interior of northwestern China, experiences extreme climatic conditions that make it a major region of soil salinization and secondary salinization, posing serious threats to local agricultural production and ecological environments. Cotton is the most widely planted economic crop under mulched drip irrigation in Xinjiang, with nearly half of local farmers cultivating it as a primary source of income. In Southern Xinjiang (hereafter "Southern Xinjiang"), high-mineralization shallow groundwater and intense evaporation cause severe soil salt accumulation in mulched drip-irrigated cotton fields, particularly when the groundwater table is shallow (<100 cm). Although cotton possesses relatively strong salt tolerance, salinity still significantly affects seed germination and seedling growth. While mulched drip irrigation demonstrates strong adaptability to saline soils and promotes root zone desalination, water savings, and yield increases, its long-term application combined with unreasonable irrigation regimes and high-mineralization irrigation water has led to prominent secondary salinization problems. Consequently, farmers are forced to adopt non-growth period flood irrigation for salt leaching to ensure the sustainable development of mulched drip irrigation technology.

Subsurface drainage represents a highly effective technology for resolving waterlogging and salinization problems and is considered a fundamental measure for saline soil improvement, offering dual functions of drainage and groundwater level control while saving water and land compared to conventional drainage. Numerous scholars have conducted extensive research on its salt leaching effects, model simulation, optimization of drainage performance parameters, and impacts on crop reproductive growth. However, few reports have addressed soil salinity conditions in Southern Xinjiang' s high-temperature, high-evaporation salinized cotton fields where subsurface pipes are installed in the saturated zone. Building on existing research, this study conducted subsurface drainage improvement experiments in long-term mulched drip-irrigated cotton fields with high groundwater levels and salinization in Southern Xinjiang to explore the response of soil salinity throughout the entire growth period to different pipe layout parameters and the benefits of irrigation leaching under subsurface drainage in this region' s unique environment. This paper analyzes soil salinity conditions and irrigation leaching effects in salinized cotton fields after subsurface pipe installation, discusses the key roles of subsurface drainage technology in salt control and discharge, and determines appropriate pipe layout parameters for high-groundwater-level salinized cotton fields in Southern Xinjiang, aiming to provide a basis for saline soil improvement in arid regions and the promotion of subsurface drainage technology in Southern Xinjiang.

2 Materials and Methods

2.1 Study Site Description

The experiment was conducted in a long-term mulched drip-irrigated cotton field at the 16th Regiment of Alaer City, Xinjiang Production and Construction Corps (80°50 50 E, 40°26 34 N). The site is adjacent to the Aksu River to the north, Shengli Reservoir to the east, and Shangyou Reservoir to the west [Figure 1: see original paper]. The region has an arid climate with an elevation of 1025 m, mean annual precipitation of 82.5 mm, mean annual evaporation of 2558.9 mm, mean sunshine duration of 8.3 $h \cdot d^{-1}$, and an average temperature of 22.3 °C during the cotton growth period. The groundwater table fluctuates around 1.0 m. The soil is primarily sandy loam with strong permeability, bulk density of 1.66 $g \cdot cm^{-3}$ in the 0–100 cm layer, field capacity of 34.95% (volumetric), and saturated water content of 42.55%.

2.2 Experimental Design and Agronomic Management

Following consistent winter-spring irrigation practices (November–March), subsurface drainage engineering was implemented after cotton harvest in 2015. The experiment employed a factorial design with two factors: pipe spacing and burial depth. Three spacing levels (10 m, 20 m, and 30 m) and two depth levels (0.8 m and 1.1 m) were established, plus a control treatment (no drainage), totaling seven treatments .

Pipes were 110 mm diameter corrugated polyvinyl chloride (PVC) with perforations covering >250 $cm^2 \cdot m^{-2}$ area, wrapped in two layers of non-woven fabric. All pipe ends connected to a collector pipe (200 mm diameter). Trenches were excavated to design depth with 30 cm bottom width, lined with filter material, then backfilled with the pipe and additional filter material, with layered compaction except for the filter-surrounded soil. The designed slope was 1.5‰ for lateral pipes and 3‰ for collector pipes, discharging into a reservoir with a small pumping station operating on a "discharge when water present" principle.

The cotton variety was "Tamian 2." Drip tape was laid in a wide-narrow row configuration (66 cm + 11 cm) with 11 cm plant spacing, positioned in the center of wide rows under plastic mulch [Figure 2: see original paper] [Figure 3: see original paper]. Irrigation scheduling involved no irrigation during the seedling stage, two irrigations during the budding stage (375 $m^3 \cdot hm^{-2}$ each), and four irrigations during the flowering-boll stage (450 $m^3 \cdot hm^{-2}$ each). Fertilizer application totaled 800 $kg \cdot hm^{-2}$ urea and 300 $kg \cdot hm^{-2}$ potassium dihydrogen phosphate via fertigation.

2.3 Data Collection and Analysis

Soil samples were collected at nine times: pre-sowing (March 25), seedling emergence (April 25), seedling stage (May 25), budding stage (June 25), full flowering (July 25), full boll stage (August 25), and boll opening (September 25), plus post-irrigation sampling. Samples were taken at 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths. Soil salt content was determined by the drying residue method after preparing a 1:5 soil-water extract, measured with a DDSJ-308A conductivity meter. The calibration equation was $Y = 0.0044EC + 0.5438$ ($R^2 = 0.9924$), where Y is soil salt content ($g \cdot kg^{-1}$) and EC is electrical conductivity ($S \cdot cm^{-1}$). Soil desalination rate was calculated as: (initial salt content - post-leaching salt content) / initial salt content × 100%. Data were processed using Microsoft Excel 2003, SPSS 23.0 for statistical analysis, and Origin 2017 and AutoCAD 2014 for figure preparation.

3 Results

3.1 Soil Salinity Distribution During the Growth Period

In high-groundwater-level cotton fields, intense evaporation caused severe surface salt accumulation. Pre-sowing surface soil salt content reached 16.01 $g \cdot kg^{-1}$ (heavy salinization), with minimal variation across depths. During emergence and seedling stages, salt content decreased with depth. As the growth period progressed (emergence to seedling stage), the control treatment showed increased salt content while all pipe treatments decreased by 11.63%-43.00%. During budding, full flowering, and full boll stages, surface salt content remained high, with the control reaching 27.05 $g \cdot kg^{-1}$ while pipe treatments maintained root zone (0-60 cm) salt content below 13.61 $g \cdot kg^{-1}$. The W1D1 treatment showed the lowest salt content at 3.89 $g \cdot kg^{-1}$. Deep soil (60-100 cm) maintained low salt content (2.85-4.13 $g \cdot kg^{-1}$), significantly lower than the root zone ($P < 0.05$).

By the boll opening stage, root zone salt content in the control increased by 11.63% compared to pre-sowing, while all pipe treatments decreased by 5.15%-36.72%. Under subsurface drainage, salt-affected cotton fields undergo continuous salt accumulation-discharge dynamics. When discharge exceeds accumulation, desalination occurs. The equilibrium point—where discharge and accumulation rates balance—represents the salt control effect of subsurface pipes. This equilibrium point is influenced by climate, irrigation, pipe parameters, and initial salinity. With other factors constant, results showed that increasing pipe spacing raised both the equilibrium point value and its range, reducing salt control effectiveness. All spacing treatments showed significant differences in equilibrium point values and ranges ($P < 0.05$).

3.2 Soil Salinity Distribution Patterns After Irrigation

Irrigation during the growth period primarily meets crop water and nutrient needs. Analysis of pre- and post-irrigation soil samples revealed distribution patterns under the mulched drip irrigation-subsurface drainage system. Using data from the second (budding) and fourth (flowering-boll) irrigations, half-profile salt distribution maps were generated. Pre-irrigation salt distribution showed vertical surface accumulation, with the control significantly higher than pipe treatments. After the second irrigation, all pipe treatments except W3D2 showed positive desalination rates, while the control exhibited negative rates (salt accumulation). Average desalination rates correlated negatively with pipe spacing: W1D1 > W2D1 > W3D1 and W1D2 > W2D2 > W3D2, reaching extremely significant levels ($P < 0.01$). The fourth irrigation showed similar patterns, with W1D1 and W1D2 demonstrating the best leaching effects ($P < 0.05$). Post-irrigation salt profiles showed low-middle, high-end patterns, with drip tape positions (50 cm from film edge) creating leached zones. Without subsurface pipes, irrigation induced salt return; with pipes, irrigation achieved leaching effects that improved as spacing decreased.

3.3 Numerical Analysis of Pipe Layout Parameters

Differential and regression analyses of soil desalination rates were performed using $P < 0.05$ as the significance level and $P < 0.01$ as the extremely significant level. Difference analysis showed that when depth was fixed at 0.8 m, all mean differences between spacings were positive, indicating decreasing desalination rates with wider spacing. Differences between 10 m and 20 m, and between 10 m and 30 m, reached significant or extremely significant levels ($P < 0.05$ or $P < 0.01$), while differences between 20 m and 30 m were not significant. At 1.1 m depth, similar patterns emerged. However, differences between 0.8 m and 1.1 m depths at the same spacing showed no consistent pattern and were not significant.

Regression analysis yielded the equation: Desalination rate = $-0.807X_1 + 70.751X_2 + 18.183$ ($R^2 = 0.892$), where X_1 is spacing and X_2 is depth. Standardized coefficients showed spacing had a more significant effect than depth. Based on these analyses, W1D1 (10 m spacing, 0.8 m depth) and W1D2 (10 m spacing, 1.1 m depth) were identified as optimal configurations. However, considering that 20 m spacing also provides good salt discharge and control effects, we recommend 20 m as a reasonable spacing for non-heavily salinized cotton fields based on economic considerations.

4 Discussion

Long-term mulched drip-irrigated cotton fields in Southern Xinjiang experience varying degrees of salt accumulation after the growth period. To reduce soil salt content for better emergence the following year, winter-spring irrigation is implemented before sowing for moisture conservation and salt leaching. Our results showed that the control treatment accumulated salt by the boll opening stage (mean salt content increased by 11.63% compared to pre-sowing), consistent with findings by Su Litan et al. In contrast, subsurface pipe treatments decreased salt content, transforming annual salt accumulation into desalination, which could theoretically reduce or eliminate winter-spring irrigation water requirements.

After crop establishment, cotton growth is promoted by low salt and inhibited by high salt, making salt stress a key factor limiting growth and yield. Zhu Yankai et al. found that cotton yield, boll number per plant, and boll weight decreased significantly when salt content exceeded 5.3 $g \cdot kg^{-1}$, but showed no significant difference from low-salt soils below this threshold. Our results demonstrated that subsurface pipes provided a suitable environment for cotton emergence and seedling growth, with root zone salt content in most treatments remaining below the 5.3 $g \cdot kg^{-1}$ yield reduction threshold during critical growth stages, except for W3D1 and W3D2.

While numerous studies have examined leaching effects with subsurface pipes in saturated zones and analyzed soil salt changes across growth stages, no unified framework exists for quantitatively assessing salt control effects. This study introduces the concept of equilibrium point range and domain values as quantitative indicators for evaluating saturated-zone pipe performance across growth stages. Data analysis revealed that increasing pipe spacing raises the equilibrium point value and its fluctuation range, diminishing salt control effectiveness.

Without subsurface pipes, post-irrigation salt return occurred; with pipes, irrigation achieved leaching objectives. Both salt discharge and leaching effects improved as spacing decreased, with 10 m spacing identified as optimal, consistent with Wang Zhenhua et al. Depth effects between 0.8 m and 1.1 m were not significant, with spacing showing more pronounced effects than depth, aligning with Heng Tong et al. However, 20 m spacing still achieved good salt control effects, and considering the increased engineering costs of narrower spacing, we recommend 20 m as a reasonable spacing for non-heavily salinized fields.

5 Conclusions

1) Subsurface drainage systems enable cotton growth in suitable soil salinity environments in high-groundwater-level saline cotton fields of Southern Xinjiang, transforming annual salt accumulation into desalination by the growth period’ s end and theoretically reducing winter-spring irrigation water requirements. Soil salt equilibrium point values and ranges decrease with narrower pipe spacing, improving salt control effectiveness.

2) Without subsurface pipes, salt return occurs after irrigation during the growth period; with subsurface pipes, irrigation produces salt leaching effects that improve as pipe spacing decreases.

3) Differential and regression analyses of soil desalination rates indicate that

W1D1 (10 m spacing, 0.8 m depth) is the optimal configuration in our experimental design. Pipe spacing exerts a more significant effect on desalination rate than burial depth.

4) Since 20 m spacing also provides good salt discharge and control effects, we recommend this as a reasonable spacing for non-heavily salinized cotton fields based on economic considerations.

These results provide a theoretical basis for saline soil improvement in arid regions and the promotion of subsurface drainage technology in Southern Xinjiang.

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

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