Variations of Soil Salinity and Cotton Growth under Six-Years Mulched Drip Irrigation

Wenhao Li 1,2,3, Zhenhua Wang 1,2,*, Jinzhu Zhang 1,2 and Ningning Liu 1,2

1 College of Water & Architectural Engineering, Shihezi University, Shihezi 832000, China; lwk8510012@163.com (W.L.); xjshzzjz@shzu.edu.cn (J.Z.); lndmail@163.com (N.L.)
2 Key Laboratory of Modern Water-Saving Irrigation of Xinjiang Production & Construction Group, Shihezi University, Shihezi 832000, China
3 College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China

* Correspondence: wzh2002027@shzu.edu.cn

Abstract: The lowering of salt content in the field, especially in arid areas, after consecutive application of mulched drip irrigation (MDI) is of vital importance for sustainable cotton plantation. To elucidate the effects of long-term MDI on soil properties and cotton growth, this paper systematically monitored the soil salinity, ion concentrations and the yield of cotton in the field using MDI consecutively for six years in a typical oasis in Xinjiang, China. The results showed that MDI could significantly change salt distribution in the cotton field. During the six years tested, the soil salt content using MDI declined fast at first, and then the decline rate gradually decreased. In the 1st and 2nd year, the average salt content within 0–100 cm soil layer was larger than 20 g kg\(^{-1}\), which belonging to the saline soil. Then the salt content decreased to 10–20 g kg\(^{-1}\) in the 3rd and 4th year, and the cotton field declined to heavily saline soil. After 5 years of MDI, the soil turned to non-salinized. The Cl\(^–\) and SO\(_4^{2–}\) equivalence ratio (CSER) also decreased with the increase of application years of MDI. Saline-alkaline land developed from chloride-sulphate solonchak (0.2 < CSER < 1) into sulphate solonchak (CSER < 0.2) after 6 years of MDI. The survival rate of the cotton increased from 4.48% (1 year of MDI) to 76.3% (6 years of MDI), and the yield increased from 72.43 kg ha\(^{-1}\) to 76.05% of the country’s total area in 2019, total yield proportion for 84.89%.

Keywords: mulched drip irrigation; soil salinity; application years; sustainable farming

1. Introduction

Sustainable and efficient utilization of saline-alkaline soils is a critical step toward increasing the amount of arable land and its agricultural production capacity, protecting food security in many parts of the world, including maintaining a minimum of 1.8 billion acres of crop production in China [1]. The saline-alkaline soil area in Xinjiang is 1.23 × 10\(^6\) ha, which accounts for nearly one third of total saline-alkaline soil in China [2,3]. Most saline-alkaline soil in Xinjiang distributed in oases. The technology of mulched drip irrigation (MDI) has greatly promoted the development of the regional cotton industry after it was invented in the oasis of Xinjiang in 1996 [4,5]. According to the cotton production report issued by the National Bureau of Statistics, Xinjiang’s cotton planting area accounted for 76.05% of the country’s total area in 2019, total yield proportion for 84.89%.
However, based on the concept of combined planning wetting layer and targeting at water-saving, most experts and scholars according to tests determined that the drip irrigation period for the cotton field in Xinjiang was about 5–7 d or the whole growth period needed about 12 irrigation times or 345–390 mm of irrigation quota [6]. Theoretically, the MDI technology can only adjust salt distribution in soil to create a suitable environment for root growth temporarily. In the long run, salts inputted into soil by irrigation will concentrate in deeper soil layers. Therefore, the sustainable development problems of MDI technology, especially its application in saline-alkaline land, are questioned by experts and scholars. The evolution of salinity in the cotton field under the long-term MDI has attracted wide attention [6].

A few scholars have studied the distribution and dynamics of salinity in saline-alkaline cotton fields under the long-term MDI. Some results suggested that MDI resulting in salinity decreased year-by-year of cultivation layer (0–40 cm or 0–60 cm), and that desalination of the whole aeration zone even occurred in partial shallow groundwater zones [6,7]. On the other hand, some researchers pointed out that high-frequency and low-volume drip irrigation may desalinate the surface soils during the cotton growth period, and salts concentrated in 0–40 cm soil layer at bare land, i.e., in the middle of the two plastic films without mulching. However, after the cotton harvest, increasing soil salinity has been observed throughout the 0–60 cm layer, resulting in a net accumulation of salinity in cotton fields with drip irrigation [2,8,9]. According to the study of Ning, the long-term MDI in different hydrological years resulted in the alternation of soil salt desalination and salt accumulation [10]. While the short-term behaviors of salt have been well-reported, the development characteristics under long-term MDI in cotton fields remain unclear. Most relevant studies have only discussed changes in salt; few have explored the ionic migration and changes of salt composition. This study attempted to determine the evolution characteristics of salt in cotton fields in saline-alkaline oases and the response relationship of yield under existing MDI.

The objectives of this paper were: (1) the distribution and variation of soil salinity using six years of MDI; (2) the effects of long-term MDI on ions composition, sodium adsorption ratio (SAR) and Cl$^{-}$ and SO$_4^{2-}$ equivalence ratio (CSER); and (3) changes of cotton survival rate and yield when consecutively applying MDI.

2. Materials and Methods

2.1. Experimental Design

The research area is a typical oasis saline-alkali area, locating at Paotai Town, Shihezi City, in the Xiayedi Irrigation District of the Manas River Basin (Figure 1a–c). The region has a typical arid continental climate, with an average annual rainfall of 215 mm. Annual rainfalls from 2014 to 2019 were 131.7, 151.4, 168.3, 219.6, 204.6 and 225.7 mm, respectively. The rainwater salinity in 2014 was 0.13 g L$^{-1}$. A piece of strip field was selected as the research object, covering an area of 4.67 ha (Figure 1d), which was a primary saline-alkali wasteland before reclamation. MDI has been used to grow cotton in this area since 2014. One plastic sheet along with two drip irrigation laterals for every six rows of cotton was applied as planting pattern. The paired rows of cottons were 110 mm apart from each other while it was 660 mm between unpaired rows and 600 mm between plastic sheets (Figure 2). In order to be close to the actual production, the experiment took the farmers’ high-yield experience as the basis for determining the irrigation amount. The irrigation periods mainly depend on the water consumption law of cotton; at the same time, the rotation of irrigation in the irrigation area should be considered. The irrigation schedule from 2014 to 2019 is shown in Table 1. Irrigation water was imported from the Manas River, and the average salinity during the 2014–2019 irrigation season were 0.73, 0.65, 0.77, 0.75, 0.75 and 0.72 g L$^{-1}$, respectively. The cotton field was managed with integration of water and fertilizer technology, and the average annual N and K application rates were 486 kg ha$^{-1}$ and 203 kg ha$^{-1}$, respectively.
The texture and chemical properties of soil in the field were analyzed since April 2014. The distribution of soil particles in each layer was measured by the hydrometer and the soil texture was classified according to the results of literature [11]. The bulk density of the soil was tested by the cutting-ring method. The basic physical properties of the top 100 cm of soil are listed in Table 2. Soil texture was relatively uniform in the cultivated layer. The average salt content within the 0–100 cm soil layer was 24.84 g kg$^{-1}$, so we categorized it as the saline soil [12]. The average contents of Na$^+$, Cl$^-$, Ca$^{2+}$, Mg$^{2+}$, and SO$_4^{2-}$ were 9.39 g kg$^{-1}$, 0.49 g kg$^{-1}$, 1.82 g kg$^{-1}$, 1.22 g kg$^{-1}$, and 0.78 g kg$^{-1}$, respectively. The Cl$^-$:SO$_4^{2-}$ equivalence ratio was 0.87, and the saline-alkaline soil in this cotton field was in detail classified as the chloride-sulfate saline soil [12].
Table 1. The irrigation schedule of cotton in study area in 2014–2019.

| Year | Date  | Rate /mm | Date  | Rate /mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Date  | Rate/mm | Total/mm |
|------|-------|----------|-------|----------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|
| 2014 | 21 Apr| 205      | 17 May | 89       | 12 Jun.| 63      | 25 Jun.| 72      | 4 Jul. | 64      | 16 Jul.| 89      | 27 Jul.| 86      | 12 Aug.| 69      | 26 Aug.| 88      | 26 Aug.| 826     |
| 2015 | 24 Apr| 189      | 19 May | 60       | 14 Jun.| 77      | 25 Jun.| 61      | 6 Jul. | 67      | 15 Jul.| 81      | 26 Jul.| 75      | 11 Aug.| 62      | 25 Aug.| 91      | 764    |
| 2016 | 22 Apr| 151      | 20 May | 79       | 13 Jun.| 83      | 24 Jun.| 102     | 5 Jul. | 89      | 17 Jul.| 93      | 28 Jul.| 71      | 10 Aug.| 74      | 26 Aug.| 0       | 742    |
| 2017 | 25 Apr| 136      | 16 May | 39       | 15 Jun.| 70      | 27 Jun.| 57      | 5 Jul. | 117     | 15 Jul.| 78      | 24 Jul.| 106     | 11 Aug.| 108     | 23 Aug.| 78      | 787    |
| 2018 | 26 Apr| 124      | 15 May | 27       | 17 Jun.| 79      | 26 Jun.| 112     | 5 Jul. | 91      | 17 Jul.| 70      | 26 Jul.| 112     | 9 Aug. | 117     | 27 Aug.| 0       | 730    |
| 2019 | 24 Apr| 143      | 14 May | 27       | 14 Jun.| 77      | 28 Jun.| 93      | 7 Jul. | 76      | 18 Jul.| 97      | 29 Jul.| 73      | 14 Aug.| 89      | 28 Aug.| 105     | 780    |

Table 2. Soil texture and bulk density of the top 100 cm of soil in the sampling location.

| Depth/cm | 0–5 | 15–20 | 35–40 | 55–60 | 75–80 | 95–100 |
|----------|-----|-------|-------|-------|-------|-------|
| Sand percentage (2-0.02 mm)/% | 74.65 | 87.67 | 89.57 | 88.32 | 87.43 | 69.57 |
| Silt percentage (0.02–0.002 mm)/% | 13.00 | 7.77  | 4.69  | 7.25  | 5.74  | 16.83 |
| Clay percentage (<0.002 mm)/% | 12.35 | 4.56  | 5.74  | 4.43  | 6.83  | 13.60 |
| Soil texture | Sandy loam | Sandy | Sandy | Sandy | Loamy sand | Sandy loam |
| Bulk density/g cm$^{-3}$ | 1.28 | 1.47  | 1.49  | 1.48  | 1.49  | 1.52  |
Spot-sampling at a fixed time were conducted from 2014 to 2019 and each annual sampling campaign was arranged. In order to accurately determine the variations in soil salinity during the growth period of cotton using MDI, samples were collected in the middle of each month from April to October each year. Irrigation was stopped two days before sampling, and the sampling time was required that there was no rain during the previous 4–5 days.

2.2. Experimental Methods

2.2.1. Sampling Processes and Methods

The three sampling zones in the cotton field were located at \( \frac{1}{4}, \frac{1}{2}, \) and \( \frac{3}{4} \) of the diagonal distance from the northeast corner to the southwest corner of the field (Figure 1d). All sampling zones were marked after the first sampling to ensure consistency. Three sampling points were chosen in each sampling zone: one was located under the drip irrigation tape, and one was in the middle of the narrow rows, and the other was between the mulching films (Figure 2). Sampling with a soil drill may have a certain error in depth. Soil samples were collected at 0–3, 20 ± 3, 40 ± 3, 60 ± 3, 80 ± 3, 100 ± 3, 120 ± 3 and 140 ± 3 cm.

2.2.2. Soil Salinity and Ions

The samples were air-dried, ground, and screened through a 1-mm sieve, which then were mixed with water. The mass ratio of soil to water was 1:5, the leachate was filtered after shaking for 15 min. The electrical conductivity (EC) value of the leachate from each sample was tested using a DDS-11A digital display conductivity meter (manufactured by Shanghai Leici Ltd., Shanghai, China). The EC \(_{1:5}\) value was corrected to the corresponding salinity mass fraction (g kg\(^{-1}\)) of the residual drying method, and all samples were converted into salinity mass fraction (g kg\(^{-1}\)). According to the method described by Sepahvand [13], the concentration of Na\(^+\) in the samples was tested by the flame photometer. The concentrations of Cl\(^-\) and SO\(_4^{2-}\) were tested by the AgNO\(_3\) titration method and EDTA indirect titration method. At last, Mg\(^{2+}\) and Ca\(^{2+}\) abundances were tested by the complexometric titration method [14]. All test results were converted in terms of g kg\(^{-1}\).

2.2.3. SAR and Cl\(^-\):SO\(_4^{2-}\)

The annual average was calculated using the same depth data for the same MDI year. There is a proportional linear relationship between the sodium absorption ratio (SAR) of the soil and its percentage exchangeable sodium (ESP) [15]. In this study, SAR was used as an evaluation index of cotton field alkalinity under long-term MDI. The standard equation for SAR (mol kg\(^{-1}\))\(^{0.5}\) depends on the ratio concentrations (mol kg\(^{-1}\)) of Na\(^+\) to Ca\(^{2+}\) and Mg\(^{2+}\) ions in soil: SAR = Na\(^+\)/[(Ca\(^{2+}\) + Mg\(^{2+}\))/2]\(^{1/2}\) [13]. In this study area, Cl\(^-\) and SO\(_4^{2-}\) were the main anions. Since Cl\(^-\) easily migrates with water, while SO\(_4^{2-}\) is resistant to this process, Cl\(^-\) and SO\(_4^{2-}\) equivalence ratio (CSER) can be used to evaluate anion leaching performance under MDI (equivalence ratio, the ion milligram equivalent of 1 kg soil is equal to the ion content in 1 kg soil divided by the milligram equivalence of this ion). At the same time, saline-alkaline lands can be classified by equivalence ratio [12], which also can help land managers, farmers, and researchers to explain the influences of long-term MDI on saline-alkaline lands.

2.2.4. Cotton Growth and Yield

The average survival rate and the actual yield of cotton can also reflect the improvements of saline-alkaline land under long-term MDI. In order to calculate the survival rate of cotton, three pieces of discontinuous mulching film with 3 m long were randomly selected, and the actual number of cotton plants in each section was counted during the boll-opening period. According to the known plant distance, it was calculated that the nominal number of cotton per section was 180 plants and 6 rows per film. A total of 540 cotton plants should have been planted in these three parts, providing the baseline value. The actual number of cotton plants that reached boll-opening period was divided by this nominal number.
to get an emergence rate (%). At the same time, actual cotton production (kg ha\(^{-1}\)) was monitored from 2014 to 2019.

2.2.5. Data Analysis

The regression analysis method was used to investigate the correlations between the average salt content of 0–140 cm soil layers, survival rate, yields, and MDI years. The best fitting function was selected based on the coefficient of determination (R\(^2\)). Regression analysis was performed with Origin 9.1 (OriginLab, Inc., Hampton, MA, USA). The measurement data were analyzed using the one-way analysis of variance (ANOVA) method. By calculating Pearson correlation coefficient, the correlations between survival rate, yield and MDI years, soil average salinity, SAR and CSER of the soil were determined. And SPSS Statistics 20.0 was used for statistical analysis (IBM, Armonk, NY, USA).

3. Results and Analysis

3.1. Soil Salinity Distribution

Figure 3 showed the distribution of soil salt in April and October in the first year of MDI, and the change of salt in the cotton field using 1–6 a of MDI were shown in Figure 4. The application of MDI significantly changed the salt distribution characteristics (Figure 3). This means that the salt contents in the MDI zone were lower after irrigation and salt accumulated in the bare land between plastic films. After 1 a using MDI, the average salt content of soil surface layer under drip irrigation lateral was 40.57 g kg\(^{-1}\), and the salt content of bare surface layer between plastic films was 72.46 g kg\(^{-1}\). After the first MDI period (from April to October), the soil salinity of 0–80 cm was decreased overall, and the average salt content decreased from 28.79 g kg\(^{-1}\) to 25.93 g kg\(^{-1}\). Part of the salt accumulated in soil at 80–140 cm, the salt content increased from 8.87 g kg\(^{-1}\) to 10.86 g kg\(^{-1}\), and part of the salt was leached into the deeper layer of the soil.

Figure 3. Salt distribution in 0–140 cm soil layer from drip irrigation belt to bare land between the mulching films in the first year of MDI.

Figure 4a revealed that salts were concentrated on the surface in the saline-alkaline cotton field from the beginning of the study until 3 a. The salt content of all depths generally decreased over time with the application of MDI, and the salt content was relatively uniformly distributed in the studied soil layers within 4 a period. The salt content was 52.65–58.49 g kg\(^{-1}\) in the surface layer after 1 a and decreased to 11.00–14.23 g kg\(^{-1}\) in the period 3 a, and the salt content of 80 cm and soil layers above decreased to less than 5.51 g kg\(^{-1}\). The salt content of 0–140 cm soil layer in saline-alkaline cotton field basically remained below 6.21 g kg\(^{-1}\) after 4 a.
The first-order decay exponential function of the salt regression was as follows: 
\[ y = 31.54 \times \exp(-x/2.80) - 0.58 \quad (R^2 = 0.99, \text{Figure 4b}) \]
The results showed that the salt content decreased with the extension of MDI application periods and the interannual desalination decreased year by year, showing a negative exponential correlation. According to the classification standard of saline-alkali soil land determined by Chhabra, and combining with the salinity regression results that the salt content of the 0–100 cm soil layer was more than 20 g kg\(^{-1}\) when applying MDI for 1.23 a, the cotton field was classified as a saline soil [12]. Few plants can survive under these conditions during this period. During the 3 a and 4 a, the cotton fields declined to heavily saline soil (10–20 g kg\(^{-1}\)), which severely inhibited crop growth [16]. By the end of 7 a (x = 6.24 a), the cotton field equivalent to moderately saline soil (3–10 g kg\(^{-1}\)) had a certain degree of inhibition on crop growth. Eventually, the cotton field fell into the non-salinized soil category after 8 a, and crops could grow normally during this period.

3.2. Spatiotemporal Migration Patterns of Ions

The variation of the distribution of five ions (Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), SO\(_4^{2-}\) and Cl\(^-\)) in the soil profile during the period 1–6 a was shown in Figure 5. The content of Na\(^+\) was the highest among the five kinds of ions in cotton field, while the content of Na\(^+\) in the deep soil was obviously lower, and it was only 2.95–3.76 g kg\(^{-1}\) below 100 cm (Figure 5a). The chemical properties of magnesium and calcium in the soil are similar [17]. At 1 a, the Ca\(^{2+}\) content of the surface layer was 2.70–2.92 g kg\(^{-1}\), and the Mg\(^{2+}\) content was 1.70–1.83 g kg\(^{-1}\). The contents of the two cations were lower in deeper soil, with lower than 1.08 g kg\(^{-1}\) of Ca\(^{2+}\) and 0.89 g kg\(^{-1}\) of Mg\(^{2+}\) below 60 cm (Figure 5b,c). SO\(_4^{2-}\) content in the surface layer was 0.87–0.90 g kg\(^{-1}\) at 1 a, whereas the content below 80 cm was 0.42–0.59 g kg\(^{-1}\) (Figure 5d). The concentration of relatively active ion Cl\(^-\) in the surface soil in 1 a was 0.56–0.57 g kg\(^{-1}\), which is lower than 0.31 g kg\(^{-1}\) below 100 cm [18]. In the whole process of applying MDI, five kinds of ions’ contents decreased year by year, and the distribution was more uniform in different soil layers (Figure 5e).

3.3. Changes in SAR and CSER

The SAR and CSER values of 0–60 cm soil (main root layer), 0–100 cm soil (root layer) and 0–140 cm (whole monitoring profile) during periods 1–6 a were shown in Table 3, and the SAR decreased over time for all subdivisions of the profile. The SAR of 0–60 cm layer after 6 a was 55.0% lower than that at 1 a. Meanwhile, the SAR values within 0–100 cm and 0–140 cm soil layers decreased by 54.7% and 52.5%, respectively. In the case of long-term application of MDI, the relative activity of soil Na\(^+\) exchange reaction decreased gradually, and the alkalization degree of cotton field also showed a downward trend. At the same time, it also reflected the change of cationic composition of soil salt.
Agronomy 2021, 11, x FOR PEER REVIEW 7 of 15

cotton field fell into the non-salinized soil category after 8 a, and crops could grow normally during this period.

### 3.2. Spatiotemporal Migration Patterns of Ions

The variation of the distribution of five ions (Na$^+$, Ca$^{2+}$, Mg$^{2+}$, SO$_4^{2−}$ and Cl$^−$) in the soil profile during the period 1–6 a was shown in Figure 5. The content of Na$^+$ was the highest among the five kinds of ions in cotton field, while the content of Na$^+$ in the deep soil was obviously lower, and it was only 2.95–3.76 g kg$^{-1}$ below 100 cm (Figure 5a). The chemical properties of magnesium and calcium in the soil are similar [17]. At 1 a, the Ca$^{2+}$ content of the surface layer was 2.70–2.92 g kg$^{-1}$, and the Mg$^{2+}$ content was 1.70–1.83 g kg$^{-1}$. The contents of the two cations were lower in deeper soil, with lower than 1.08 g kg$^{-1}$ of Ca$^{2+}$ and 0.89 g kg$^{-1}$ of Mg$^{2+}$ below 60 cm (Figure 5b, c). SO$_4^{2−}$ content in the surface layer was 0.87–0.90 g kg$^{-1}$ at 1 a, whereas the content below 80 cm was 0.42–0.59 g kg$^{-1}$ (Figure 5d).

The concentration of relatively active ion Cl$^−$ in the surface of soil in 1 a was 0.56–0.57 g kg$^{-1}$, which is lower than 0.31 g kg$^{-1}$ below 100 cm [18]. In the whole process of applying MDI, five kinds of ions’ contents decreased year by year, and the distribution was more uniform in different soil layers (Figure 5e).

![Figure 5. A contour plot showing the changes in ions content (g kg$^{-1}$) over the six study periods from the surface to depth of 140 cm. Figure (a–e) represent the distribution of (a) Na$^+$, (b) Ca$^{2+}$, (c) Mg$^{2+}$, (d) SO$_4^{2−}$ and (e) Cl$^−$, respectively.](image)

| Depth/cm | MDI Application Period |
|----------|-----------------------|
|          | 1 a | 2 a | 3 a | 4 a | 5 a | 6 a |
| 0–60     | 1.99 | 1.57 | 1.18 | 1.02 | 0.95 | 0.83 |
| 0–100    | 1.81 | 1.37 | 1.07 | 0.98 | 0.94 | 0.75 |
| 0–140    | 1.64 | 1.30 | 0.97 | 0.94 | 0.89 | 0.70 |

| Depth/cm | CSER |
|----------|------|
| 0–60     | 0.86 |
| 0–100    | 0.87 |
| 0–140    | 0.81 |
CSER of 0–60 cm, 0–100 cm, and 0–140 cm depths decreased with the increase of drip irrigation years (Table 3), and CSER of 0–100 cm layer decreased the fastest from 0.87 at 1 a to 0.47 at 6 a. In the process of “washing salt” in cotton fields irrigation, Cl\(^{-}\) with relatively active chemical properties decreased faster than SO\(_4^{2-}\). The differences of ion chemical properties led to the gradual change of anion composition in the soil of long-term MDI cotton fields. The linear function of CSER regression equation was \(\text{CSER} = 0.92 - 0.08x\), \((R^2 = 0.98)\), where \(x\) is the irrigation application period (a). According to the classification standard determined by Chhabra and the regression equation of saline-alkali land, the Saline-alkali land developed from chloride-sulphate solonchak (0.2 < CSER < 1) to sulphate solonchak (CSER < 0.2) after MDI 9 a expectancy according to the regression equation \([12]\).

3.4. Survival Rate and Cotton Yield under Different Soil Salinities

The correlation analysis results of actual survival rate and yield of cotton with the years of MDI, CSER, SAR, and average soil salinity of the soil were shown in Table 4. The survival rate and yield of cotton had a significant positive correlation with the years of MDI and a significant negative correlation with the average salt content, SAR and CSER. The functional relationship of the survival rate and yield on the years of MDI, CSER, SAR, and average soil salinity is shown in Figure 6a–h.

### Table 4. Dependence analysis results of cotton survival rate and yield of cotton on the years of MDI, soil salt content, SAR and CSER, respectively.

| Variable         | Years of MDI  | Soil Salinity g kg\(^{-1}\) | SAR (mol kg\(^{-1}\))\(^{0.5}\) | CSER     |
|------------------|---------------|-----------------------------|---------------------------------|----------|
| Survival rate/%  | 0.988 \(^{1}\) | -0.939 \(^{1}\)            | -0.933 \(^{1}\)                | -0.980 \(^{1}\) |
| Yield/kg hm\(^{-2}\)| 0.984 \(^{1}\) | -0.978 \(^{1}\)            | -0.967 \(^{1}\)                | -0.990 \(^{1}\) |

\(^{1}\) Signify significant correlations for \(p < 0.01\).

The survival rate of cotton increased from 1.48% at 1 a to 76.30% at 6 a, and the output increased from 72.43 kg ha\(^{-1}\) to 4515.48 kg ha\(^{-1}\), both of them representing dramatic increases. Meanwhile, the average CSER, SAR and the soil salinity in 0–140 cm soil layer were decreased from 0.87, 1.81 (mol kg\(^{-1}\))\(^{0.5}\) and 24.84 g kg\(^{-1}\) to 0.47, 0.75 (mol kg\(^{-1}\))\(^{0.5}\) and 3.15 g kg\(^{-1}\), respectively.

The relationship between survival rate and yield was first-order decay exponential function with MDI years, the average CSER, SAR and the soil salinity in the 0–140 cm soil layer, respectively (Figure 6a–h). According to the survey, the average cost of local was about 27,000 RMB ha\(^{-1}\), and the average input subsidized by the government was about 7.3 RMB kg\(^{-1}\) from 2014 to 2019. On the basis of the regression equation, the break-even point appeared in MDI 4 a (\(x = 3.13\)), after which growing cotton became profitable. Meanwhile, the average CSER, SAR and the soil salinity in 0–140 cm soil layer were 0.60, 0.98 (mol kg\(^{-1}\))\(^{0.5}\) and 6.25 g kg\(^{-1}\). Excluding other factors, after 9 years of MDI, the average CSER, SAR and the soil salinity will decrease to 0.44, 0.69 (mol kg\(^{-1}\))\(^{0.5}\) and 0.77 g kg\(^{-1}\), respectively, and the cotton yield would increase to 6133.13 kg ha\(^{-1}\), which exceeded the average output of Xinjiang calculated by the National Bureau of Statistics, and farmers will increase their income by 617,771.85 RMB ha\(^{-1}\).
Figure 6. Cotton survival rate (Value ± SD) and yield (Value ± SD) change with the years of MDI (a,b), CSER (c,d), SAR (e,f), and average soil salinity (g,h) are represented by histograms, and the red curves are the regression curves of cotton survival rate and yield with long-term MDI, CSER, SAR, and average soil salinity, respectively.
4. Discussion

4.1. Soil Salinity Variations and Transportation Process Using MDI Consecutively

After drip irrigation, the soil water content in the direction parallel to the drip irrigation lateral was higher than that in the vertical direction [19]. Therefore, cotton field under MDI presented desalination within the film and salt accumulation between the films (Figure 3). As reported by Li et al. and Zhang et al., salt content under drip irrigation lateral was the lowest, and the result of the salt accumulation on wetting front or exposed soil surface was similar [17,20]. Aragüés et al. considered that the variation of the chloride ion and sodium adsorption rate and electrical conductivity was the same after irrigation [21]. The author further confirmed that the soil salt, ion, SAR and CSER of the long-term MDI cotton field all decreasing gradually due to the salt displacement effect of drip irrigation, and the soil salt composition was also changing (Figures 4 and 5 and Table 3).

Li et al. and Tan et al. determined the trend of soil salt content decreased after 1–2 a of MDI in spring-corn fields and former wasteland [22,23]. This was in line with the conclusion obtained in this study. However, they did not deeply analyze the characteristics of the salt decline and salt composition. A few scholars thought that the application of MDI technology would lead to soil salt accumulation. Wang et al. thought that the salt would be accumulated in the root area by the way of regulated deficit drip irrigation (irrigation quota of 420 mm) [24]; meanwhile they pointed out that great irrigation after harvest would not lead to soil salinization. Liu et al. believed that 150 mm of freshwater could be used to leach accumulated salt into the non-reproductive period [25]. The irrigation quota of MDI cotton field was 760 mm (Table 1), which was larger than the sum of the growth period irrigation quota designed by Wang et al. and the non-reproductive period salt washing quota set by Liu et al. [24,25]. Therefore, larger irrigation quota was the main factor leading to the decrease of salt content in the study area, but it also caused a waste of nearly 200 mm of water resources. Al-Muaini et al. and Chen et al. used the brackish water for irrigation, and salt accumulation occurred after the end of the growing period [26,27]. But Al-Muaini et al. also pointed out that larger amount of irrigation could inhibit salt return. Wan et al. demonstrated that the reasonable brackish water irrigation strategy would not lead to soil accumulated salt under MDI [28]. Previous results confirmed that poor quality water could lead to soil accumulation in the root zone when using drip irrigation in corn plantation [29,30]. Therefore, the suitable irrigation water quality was also an important factor in reducing salinity.

4.2. Deep Monitoring

The soil salt was leached in the deep layer by irrigation water, which might affect the regional groundwater level and salinity. The changes of groundwater level and salinity in the research area from April and October of 2014–2019 are shown in Figure 7. The groundwater level in the study area increased significantly from April to October, and then dropped again from October to April of the following year. The trend of groundwater salinity was opposite to that of groundwater level. From 2014 to 2019, the regional groundwater level was kept at 3.05–4.20 m, and the salinity was maintained at 28.0–48.9 g L⁻¹, with no significant change from year to year.

Irrigation activities had a significant impact on groundwater [31,32], and the groundwater level in the study area increased significantly from April to October of the year (Figure 7). During the irrigation season, the plain reservoir continued to store water. The infiltration of freshwater diluted the groundwater [33], and the salinity of groundwater in the study area was gradually decreased. In the non-irrigation season, the groundwater level decreased correspondingly, and resulting in groundwater salinization. This was the same as the research results of Takase and Fujihara in the coastal areas [34]. Therefore, appropriate irrigation schedule, ideal irrigation water quality and dynamic changes of groundwater were necessary for the steady increase of cotton survival rate and yield of cotton filed using long-term MDI (Figure 6).
Figure 7. The dynamic changes of groundwater level and groundwater salinity in the study area from 2014 to 2019 are represented by black and blue line, respectively.

4.3. Relationship between Cotton Growth and Soil Salt Environment

For many crops, high soil salinity will cause average farmland yields to be only 20% to 50% of record yields [35]. Cotton is a moderately salt-tolerant plant group, Ashraf summarized that the salinity threshold of cotton is 7.7 dS m\(^{-1}\) [36]. Chen, et al. used a greenhouse barrel planting experiment to determine that compared with 2.4 dS m\(^{-1}\), the soil salt content of 12.5 dS m\(^{-1}\) decreased cotton dry mass of seed content by 52%, and production increased with N fertilization at adequate rates at both low and medium soil salinities [37]. Zhang, et al. determined the cotton salt threshold by designing a barrel planting test device that controls the depth of the groundwater level [38]. Cotton salt threshold is affected by various factors such as experimental conditions and climate. This study determined that when the average CSER, SAR and the soil salinity in 0–140 cm soil layer were 0.60, 0.98 (mol kg\(^{-1}\)\(^{0.5}\)) and 6.25 g kg\(^{-1}\), the cotton survival rate was 42.59% and the cotton yield was 3156.65 kg hm\(^{-2}\). At this time, used the technology of MDI to grow cotton on saline-alkali land will generate benefits.

This study area was typical farmland of the Manas River basin, which is representative of the northern regions of Xinjiang. Meanwhile the research results obtained could be extrapolated to saline-alkaline regions in other oases. Achieving a sustainable balance of irrigation volume and irrigation water quality is essential in Xinjiang. The irrigation applied should satisfy the potential evapotranspiration of the cropland, providing enough surplus water that it can remove salts from the soil (including salts moved into the root layer by irrigation), and exclude the planned wetting layer. Any salts added to the planned wetting layer by the irrigation water must be leached fully after each growing season. However, the shortage of water resources is an important bottleneck factor restricting the development of agricultural planting in Xinjiang. Therefore, it is necessary to study the suitable irrigation schedule for cotton under different soil physical and chemical properties; and to adopt differential quota management in production practice. This would support sustainable agricultural development and large-scale promotion of efficient drip irrigation systems in saline-alkaline oasis regions, which are important for agricultural water application in the arid regions.
5. Conclusions

In this study, we monitored the variations and distributions of salt and its ion components in soil profile of saline-alkali cotton field that using MDI from 2014 to 2019. The main conclusions obtained were:

(1) The salt content was lower under the drip irrigation lateral and accumulated in the bare land between plastic films after drip irrigation, and the soil salt contents decreased gradually under long-term MDI. Within 2 a, the average salt content within 0–100 cm soil layer was above 20 g kg\(^{-1}\) (saline soil); and decreased to 10–20 g kg\(^{-1}\) after 4 a, and became heavily salinized. At the end of the 5 a, the cotton field became moderately salinized (3–10 g kg\(^{-1}\)), and eventually settled into the non-salinized soil after 6 a.

(2) The ions, SAR and equivalence ratio (\(\text{Cl}^-:\text{SO}_4^{2-}\)) in the cotton soil decreased with consecutively applying MDI. The SAR of the 0–100 cm layer after 6 a was 54.72% lower than that of the 1 a, and the equivalence ratio of the 0–100 cm layer decreased rapidly from 0.82 at 1 a to 0.44 after 6 a. The composition of salt changed year by year, and the saline-alkaline land developed from chloride-sulphate solonchak (\(0.2 < \text{Cl}^-:\text{SO}_4^{2-} < 1\)) into sulphate solonchak (\(\text{Cl}^-:\text{SO}_4^{2-} < 0.2\)).

(3) Larger irrigation quota, suitable irrigation water quality and dynamic variations of groundwater were necessary for the steady increment of cotton survival rate and yield in long-term MDI cotton field of the research area. The survival rate of cotton increased from 1.48% at 1 a to 76.3% after 6 a, while the yield increased from 72.43 kg ha\(^{-1}\) to 4515.48 kg ha\(^{-1}\). When the average CSER, SAR and the soil salinity in 0–140 cm soil layer decreased to 0.60, 0.98 (mol kg\(^{-1}\)) and 6.25 g kg\(^{-1}\) respectively, the farmers’ income was greater than their input. CSER, SAR and the soil salinity continuous decrease to 0.44, 0.69 (mol kg\(^{-1}\)) and 0.77 g kg\(^{-1}\) respectively, the cotton yield will increase 6133.13 kg ha\(^{-1}\), and exceed the average production level of cotton in Xinjiang.

Author Contributions: Conceptualization, W.L. and Z.W.; methodology, W.L. and Z.W.; software, W.L. and N.L.; validation, W.L., Z.W., J.Z. and N.L.; formal analysis, W.L. and N.L.; investigation, W.L. and N.L.; resources, Z.W. and J.Z.; data curation, W.L. and J.Z.; writing—original draft preparation, W.L. and Z.W.; writing—review and editing, W.L. and N.L.; visualization, N.L.; supervision, J.Z.; project administration, N.L. and J.Z.; funding acquisition, W.L. and Z.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (51869028, 51869027); and the Innovation Team in Key Areas of Corps, grant number (2019 CB004). The APC was funded by National Natural Science Foundation of China (51869028).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors would like to thank all members at Key Laboratory of Modern Water-Saving Irrigation of Xinjiang Production & Construction Group for monitoring and providing places and facilities in the experiments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, J.; Wang, Z.; Fan, B.; Hou, Y.; Dou, Y.; Ren, Z.; Chen, X. Investigating the proper application rate of nitrogen under mulched drip irrigation to improve the yield and quality of tomato in saline soil. Agronomy 2020, 10, 293. [CrossRef]

2. Casas, C.; Di Bella, C.E.; Lattanzi, F.A.; Schwab, M.; Clavijo, P.; Schäufele, R.; Druille, M.; Grimoldi, A.A. A highly productive grass improves chemical and biological properties but does not aggregate stability in saline-sodic lowlands in Argentina. Arch. Agron. Soil Sci. 2019, 1–14. [CrossRef]

3. Fang, S.; Tu, W.; Mu, L.; Sun, Z.; Hu, Q.; Yang, Y. Saline alkali water desalination project in Southern Xinjiang of China: A review of desalination planning, desalination schemes and economic analysis. Renew. Sust. Energ. Rev. 2019, 113, 109268. [CrossRef]
4. Wang, Z.; Fan, B.; Guo, L. Soil salinization after long-term mulched drip irrigation poses a potential risk to agricultural sustainability. *Eur. J. Soil Sci.* **2019**, *70*, 20–24. [CrossRef]

5. Li, X.; Liu, H.; He, X.; Gong PLin, E. Water–nitrogen coupling and multi-objective optimization of cotton under mulched drip irrigation in arid northwest China. *Agronomy* **2019**, *9*, 894. [CrossRef]

6. Li, M.; Du, Y.; Zhang, F.; Bai, Y.; Fan, J.; Zhang, J.; Chen, S. Simulation of cotton growth and soil water content under film-mulched drip irrigation using modified CSM-CROPGRO-cotton model. *Agric. Water Manag.* **2019**, *218*, 124–138. [CrossRef]

7. Guan, Z.; Jia, Z.; Zhao, Z.; You, Q. Dynamics and distribution of soil salinity under long-term mulched drip irrigation in an arid area of northwestern china. *Water* **2019**, *11*, 1225. [CrossRef]

8. Rohit Katuri, J.; Trifonov, P.; Arge, Y. Spatial distribution of salinity and society in arid climate following long term brackish water drip irrigated olive orchard. *Water* **2019**, *11*, 2556. [CrossRef]

9. Yang, P.; Dong, X.; Liu, L.; Yang, Q.; Zhang, Y. Soil salt movement and regulation of drip irrigation under plastic film in arid area. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 90–95. (In Chinese) [CrossRef]

10. Ning, S. Numerical Simulation on Soil Salt Accumulation in Root Zone of Cotton Field under Long-Term Film Mulched Drip Irrigation. Ph.D. Thesis, China Agricultural University, Beijing, China, 2015.

11. Morais, P.A.D.O.; Souza, D.M.D.; Carvalho, M.T.D.M.; Madari, B.E.; de Oliveira, A.E. Predicting soil texture using image analysis. *Microchem. J.* **2019**, *146*, 455–463. [CrossRef]

12. Chhabra, R. Classification of salt-affected soils. *Arid Land Res. Manag.* **2005**, *19*, 61–79. [CrossRef]

13. Sepahvand, A.; Singh, B.; Sihag, P.; Nazari Samani, A.; Ahmadi, H.; Fiz Nia, S. Assessment of the various soft computing techniques to predict sodium absorption ratio (SAR). *J. Hydraul. Eng.* **2019**, *1–12*. [CrossRef]

14. Pereira, S.L.A.; Moreira, H.; Argyras, K.; Castro, P.M.L.; Marques, A.P.G.C. Promotion of sunflower growth under saline water irrigation by the inoculation of beneficial microorganisms. *Appl. Soil Ecol.* **2016**, *105*, 36–47. [CrossRef]

15. Robbins, C. Sodium adsorption ratio-exchangeable sodium percentage relationships in a high potassium saline-sodic soil. *Irrig. Sci.* **1984**, *5*, 173–179. [CrossRef]

16. Paul, D.; Lade, H. Plant-growth-promoting rhizobacteria to improve crop growth in saline soils: A review. *Agron. Sustain. Dev.* **2014**, *34*, 737–752. [CrossRef]

17. Zhang, Z.; Hu, H.; Tian, F.; Hu, H.; Yao, X.; Zhong, R. Soil salt distribution under mulched drip irrigation in an arid area of northwestern China. *J. Arid Environ.* **2014**, *104*, 23–33. [CrossRef]

18. Diaz Caselles, L.; Hot, J.; Roosz, C.; Cyr, M. Stabilization of soils containing sulfates by using alternative hydraulic binders. *Appl. Geochem.* **2020**, *113*, 104494. [CrossRef]

19. Chen, L.; Feng, Q.; Li, F.; Li, C. A bidirectional model for simulating soil water flow and salt transport under mulched drip irrigation with saline water. *Agric. Water Manag.* **2014**, *146*, 24–33. [CrossRef]

20. Li, X.; Jin, M.; Huang, J.; Yuan, J. The soil-water flow system beneath a cotton field in arid north-west China, serviced by mulched drip irrigation using brackish water. *Hydrogeol. J.* **2015**, *23*, 35–46. [CrossRef]

21. Aregàes, R.; Medina, E.T.; Claveria, I. Effectiveness of inorganic and organic mulching for soil salinity and sodicity control in a grapevine orchard drip-irrigated with moderately saline waters. *Span. J. Agric. Res.* **2014**, *12*, 501–508. [CrossRef]

22. Li, M.; Liu, H.; Zheng, X. Spatiotemporal variation for soil salinity of field land under long-term mulched drip irrigation. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 82–87. (In Chinese) [CrossRef]

23. Tan, J.; Kang, Y.; Yao, Y.; Sun, Z.; Liu, W.; Dong, F.; Li, K. Characteristics of soil salinity and salt ions distribution in salt-affected field under mulch-drip irrigation in different planting years. *Trans. Chin. Soc. Agric. Eng.* **2008**, *59*, 42–50. (In Chinese) [CrossRef]

24. Wang, Z.; Jin, M.; Simunek, J.; van Genuchten, M.T. Evaluation of mulched drip irrigation for cotton in arid Northwest China. *Irrig. Sci.* **2014**, *32*, 15–27. [CrossRef]

25. Liu, M.; Yang, J.; Li, X.; Liu, G.; Yu, M.; Wang, J. Distribution and dynamics of soil water and salt under different drip irrigation regimes in northwest China. *Irrig. Sci.* **2013**, *31*, 675–688. [CrossRef]

26. Al-Muaiani, A.; Green, S.; Dakheel, A.; Abdullah, A.; Abou Dahr, W.A.; Dixon, S.; Kemp, P.; Clothier, B. Irrigation management with saline groundwater of a date palm cultivar in the hyper-arid United Arab Emirates. *Agric. Water Manag.* **2019**, *211*, 123–131. [CrossRef]

27. Chen, M.; Kang, Y.; Yan, S.; Liu, S. Drip irrigation with saline water for oleic sunflower (*Helianthus annuus* L.). *Agric. Water Manag.* **2009**, *96*, 1766–1772. [CrossRef]

28. Wan, S.; Kang, Y.; Wang, D.; Liu, S.; Feng, L. Effect of drip irrigation with saline water on tomato (*Lycopersicon esculentum Mill*) yield and water use in semi-arid area. *Agric. Water Manag.* **2007**, *90*, 63–74. [CrossRef]

29. Mmolawka, K. Water and solute dynamics under a drip-irrigated crop: Experiments and analytical model. *Trans. ASAE* **2000**, *43*, 1597–1608. [CrossRef]

30. Mmolawka, K.; Or, D. Root zone solute dynamics under drip irrigation: A review. *Plant Soil* **2000**, *222*, 163–190. [CrossRef]

31. Rotiroti, M.; Bonomi, T.; Sacchi, E.; McArthur, J.M.; Stefania, G.A.; Zanotti, C.; Taviani, S.; Patelli, M.; Nava, V.; Soler, V.; et al. The effects of irrigation on groundwater quality and quantity in a human-modified hydro-system: The Oglio River basin, Po Plain, northern Italy. *Sci. Total Environ.* **2019**, *672*, 342–356. [CrossRef] [PubMed]

32. Tian, Y.; Zhang, G.; Zheng, X.; Wang, Q.; Yan, M.; Bian, C. Environmental Study on the Quantitative Relationship between Precipitation, Aeration Zone Water and Groundwater in Taihang Piedmont Plain Agricultural Areas. *Ekoloji* **2019**, *28*, 4663–4669.
33. Jia, H.; Qian, H.; Zheng, L.; Feng, W.; Wang, H.; Gao, Y. Alterations to groundwater chemistry due to modern water transfer for irrigation over decades. *Sci. Total Environ.* **2020**, *717*, 137170. [CrossRef] [PubMed]

34. Takase, K.; Fujihara, Y. Evaluation of the effects of irrigation water on groundwater budget by a hydrologic model. *Paddy Water Environ.* **2019**, *17*, 439–446. [CrossRef]

35. Shrivastava, P.; Kumar, R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J. Biol. Sci.* **2015**, *22*, 123–131. [CrossRef] [PubMed]

36. Ashraf, M. Salt tolerance of cotton: Some new advances. *Crit. Rev. Plant Sci.* **2010**, *21*, 1–30. [CrossRef]

37. Chen, W.; Hou, Z.; Wu, L.; Liang, Y.; Wei, C. Effects of salinity and nitrogen on cotton growth in arid environment. *Plant Soil* **2009**, *326*, 61–73. [CrossRef]

38. Zhang, H.; Li, D.; Zhou, Z.; Zahoor, R.; Chen, B.; Meng, Y. Soil water and salt affect cotton (*Gossypium hirsutum* L.) photosynthesis, yield and fiber quality in coastal saline soil. *Agric. Water Manag.* **2017**, *187*, 112–121. [CrossRef]