



# Factors influencing usage of subsurface drainage to improve soil desalination and cotton yield in the Tarim Basin oasis in China

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## Abstract

Soil salinization is a global issue that results in soil degradation and affects the sustainable development of irrigated agriculture. A 2-year study was conducted in 2018 and 2019 to identify the effect of subsurface drainage spacing on soil moisture, salt, cotton growth, and yield under the Tarim Basin oasis in China. The tests involved three subsurface drainage treatments, with a pipe spacing of 10 m (W10), 20 m (W20), and 30 m (W30), respectively, and a drainage-absent treatment (CK). Compared with CK, subsurface drainage reduced soil salinity, resulted in better uniform water distribution and reduced inorganic salt concentration in shallow soil solution. In addition to improving soil moisture and salinity conditions, subsurface drainage increased seedling emergence rate (28%), root vigor (23%), and chlorophyll content (44%) of cotton, which in turn led to increases in cotton plant height (18%), leaf area (33%), dry matter weight (32%), and reproductive organ weight (39%), thereby resulting in high cotton yield (45%). A path analysis revealed that under subsurface drainage, the seedling emergence rate of cotton had the greatest impact on cotton yield, and subsurface drainage contributed the most to the increase in cotton yield. It increased the seedling emergence rate by reducing soil salinity. Moreover, cotton yield and next-year soil arability increased with decreasing drainage pipe spacing, suggesting that it is advantageous to adopt a drainage pipe layout with small pipe spacing when economic costs are not a concern.

## Introduction

Soil salinization is a global issue that results in soil degradation and affects the sustainable development of irrigated agriculture (Rozema and Flowers 2008; Salvati and Ferrara 2015). Salt-affected agricultural land increases annually with more than 19.5% of the irrigated lands being affected globally (FAO 2020). Xinjiang is located in northwestern China, and owing to its extremely arid climate conditions, less rainfall, and strong evaporation, shallow groundwater recharges the soil moisture. The water carries salt to the soil surface, causing the widespread distribution of soil salinization and secondary salinization. Similarly, the oasis of Tarim Basin is experiencing particularly severe soil salinization and secondary salinization due to the unique topography of

Tarim Basin as an inland basin, high salinity of soil parent material, and shallow groundwater table, with saline farmland accounting for 41.21% of the total farmland and 63.2% of the low-yield farmland (Yao 2017). Salinization hazards have seriously restricted sustainable development of local agriculture, thus making it urgent to conduct tests on saline soil improvement and promote practical applications of the suitable technique (Aragüés et al. 2015).

Since the mid-1990s, Xinjiang has gradually become one of the three major cotton-producing areas in China (Yang et al. 2020a), with cotton being the main component of the regional planting economy, and nearly half of the regional farmers are involved in cotton production (Ning et al. 2013). In particular, as cotton is the main cash crop in Xinjiang, film-mulched drip irrigation has been advocated and applied to cotton planting for more than 20 years. The transport characteristics of soil moisture and salt under film-mulched drip irrigation and their effects on the physiology, growth, and yield of cotton as well as the economic benefits of cotton have long been a focus of research (Wang et al. 2014, 2020a; He et al. 2020). Moreover, the longer the drip irrigation, the more is the accumulation of soil salt in cotton fields (Guan et al. 2019), which is bound to worsen the

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severely saline soil cultivation conditions further, resulting in many problems, such as decline in crop yield and soil arability (Singh 2015). When dealing with these problems, local farmers adopt surface irrigation to decrease soil salinity and increase water moisture content (Sun et al. 2016). In addition, research efforts have been made to explore other strategies, such as straw mulching, chemical treatments, and biological treatments, to reduce the harm of secondary soil salinization on crops to ensure sustained soil productivity (Akhter et al. 2004; Ganjegunte et al. 2018; Zahedifar and Moosavi 2019). However, these soil improvement measures have failed to remove salts from the soils, and consequently, the risk of secondary soil salinization persists under improper irrigation management (Wang et al. 2020b).

Subsurface drainage is a highly effective technique to solve the problem of flooding and salinity hazards and is considered a fundamental measure for saline soil improvement (Muirhead et al. 1996; Tian et al. 2018), suitable for both drainage and groundwater table control (Bahceci and Nacar 2010; Yu et al. 2016). Unlike traditional drainage, subsurface drainage is more water- and land-saving and has been extensively explored and applied in Australia, China, the US, India, Turkey, and some other countries (Christen et al. 2001; Evan et al. 2001; Kladivko et al. 2004; Fayrap and Ko 2012). Pipe spacing is an important parameter of subsurface drainage that directly affects the soil desalination efficiency and engineering costs. Extensive in-depth studies have been conducted on the change pattern of soil moisture and salinity conditions and crop yield in response to changing in drainage pipe spacing (Singh et al. 2006), leading to the identification of a variety of economical and highly productive spacings suitable for different scenarios (Shao et al. 2012).

Existing efforts are mainly focused on providing systematic guidance for drainage pipe layout, including providing insights into the effects of drainage pipe parameters on the drainage performance and groundwater table control (Yu et al. 2016), leaching of soil salts, ions, and nutrients, as well as crop yield (Oquist et al. 2007; Sands et al. 2008; Enciso et al. 2014; Yang et al. 2020b). However, the key factors that lead to differences in crop yield under subsurface drainage conditions and the interaction mechanism between the factors need further detailed investigation.

Given the above context, a saline cotton field that was located above a shallow groundwater table in the Tarim Basin oasis and had been under film-mulched drip irrigation for years was selected in this study to conduct 2-year tests on subsurface drainage-based soil improvement. Drainage pipes were installed considering the local, well-established cotton planting practices and agronomic management measures, followed by the measurement of soil moisture and salt distribution, cotton physiology and growth status, and the cotton yield. The main objectives of the tests were to (1)

clarify the relationship between soil water and salt environment and between crop growth and yield under the condition of subsurface drainage spacing, (2) provide scientific guidance for subsurface drainage-based saline soil improvement, and (3) determine the optimal drainage pipe spacing in the test scenarios and promote the exploration and application of subsurface drainage technology.

## Materials and methods

### Test area

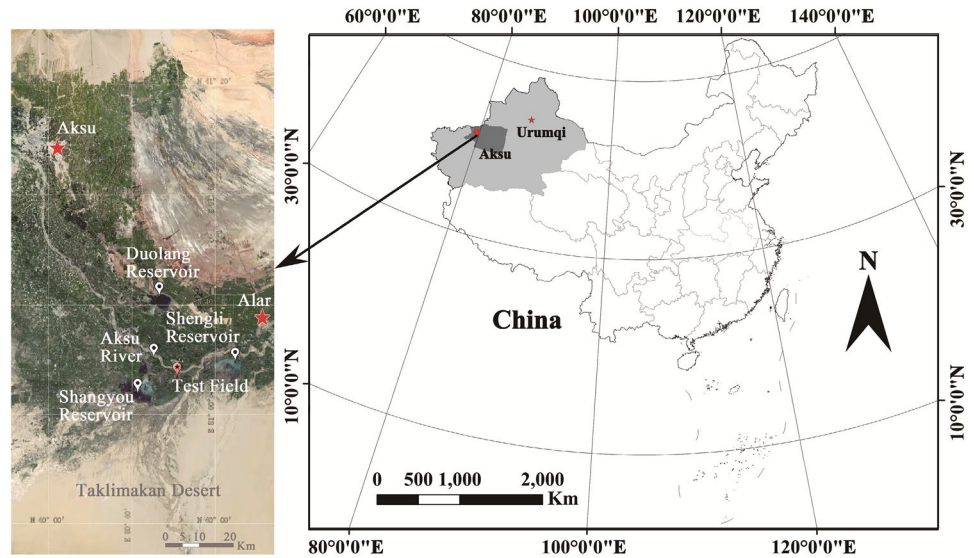
The test area was a cotton field receiving film-mulched drip irrigation for years. The field belongs to the Fifth Company of the Sixteenth Regiment of Alar City under the First Division of Xinjiang Production and Construction Corps (Fig. 1). It is situated in the northern oasis of Tarim Basin, adjacent to the Aksu River to the north, the Shengli Reservoir to the east, and the upstream reservoir to the west (80° 50' 50" E, 40° 26' 34" N). The field has an altitude of 1025 m, with an annual mean precipitation of 40.1–82.5 mm, annual mean evaporation of 1976.6–2558.9 mm, mean growing-season temperature of 22.3 °C, and mean daily sunshine duration of 8.3 h/day, all of which indicate an extremely arid climate. The meteorological data of the experimental area from 2018 to 2019 are presented in Fig. 2, taken from the Fourteenth Regiment Weather Station (81° 31' 29" E, 40° 35' 03" N). The groundwater table depth was 0.6–1.0 m, and the total dissolved solid content of shallow groundwater was generally greater than 5.0 g/L. The test field soil was mainly sandy loam at 0–60 cm and sandy soil at 60–100 cm depth and had a high permeability. Data related to the soil bulk density, saturated water content, and field water-holding capacity are presented in Table 1.

### Test design

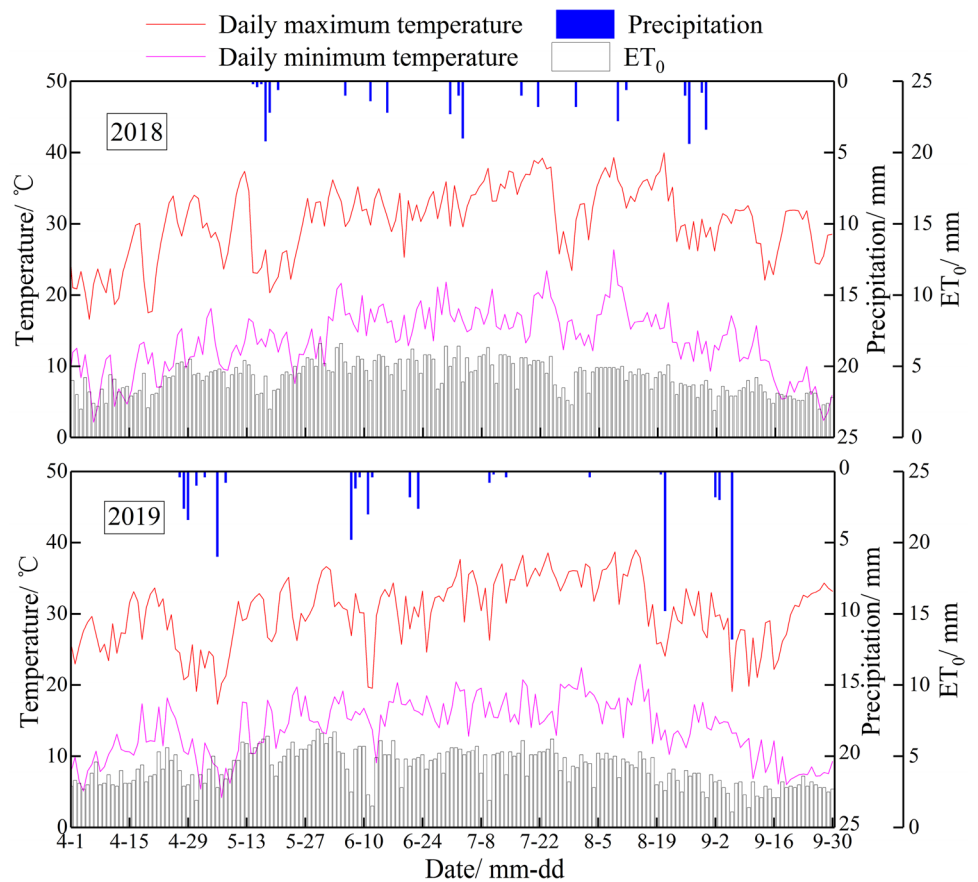
The tests involved four treatments: three with a pipe spacing of 10 m (W10), 20 m (W20), and 30 m (W30) at a burial depth of 1.1 m and one as the control treatment (CK) without drainage.

In 2017, drainage pipes were installed in the field after the harvest of seed cotton. The drainage pipes were D110 (inner diameter of 110 mm) corrugated PVC pipes, which had holes (250 cm<sup>2</sup>/m<sup>2</sup>) pre-made in the pipe surface and were externally wrapped with two layers of non-woven fabric (NWF). The ends of the corrugated pipes were connected to water collection pipes, which were 200 mm in diameter. A small excavator was deployed to make trenches to the design depth. Each trench was 30-cm wide in the bottom. First, wrapping and filtering materials were laid in the trench, followed by an NWF-wrapped drainage

**Fig. 1** Geographical location of the test field



**Fig. 2** Meteorological data of the test area



pipe. Filtering materials were placed in the side gaps and on the pipe top and backfilling soil to cover the pipe. The backfilled soil was compacted in all places except within a 20- to 30-cm distance from the wrapping and filtering materials, and the compaction was conducted in layers. The water suction and water collection pipes were laid

at of 2% and 3%, respectively. The water collection pipes were extended into a water storage pond, where water was discharged into a gutter using a small pumping station as soon as the collected water entered the pond. Soil samples were collected in triplicate at the location 1/2 W (W is the subsurface pipe spacing) of the middle drainage pipe. The

**Table 1** Soil hydraulic properties of experimental field

Soil depth, cm	0–20	20–40	40–60	60–80	80–100
Soil bulk density, g cm <sup>-3</sup>	1.51	1.48	1.43	1.34	1.36
Saturated soil moisture, %	32.1	34.0	36.9	37.7	37.9
Field water-holding capacity, %	26.3	27.1	30.8	32.3	33.7
permeability coefficient, cm day <sup>-1</sup>	11.2	8.8	8.1	8.6	7.9
Soil texture					
Sand, %	66.3	68.8	76.5	84.5	91.8
Silt, %	29.6	27.3	21.4	12.1	6.6
Clay, %	4.1	3.9	2.1	3.5	1.5

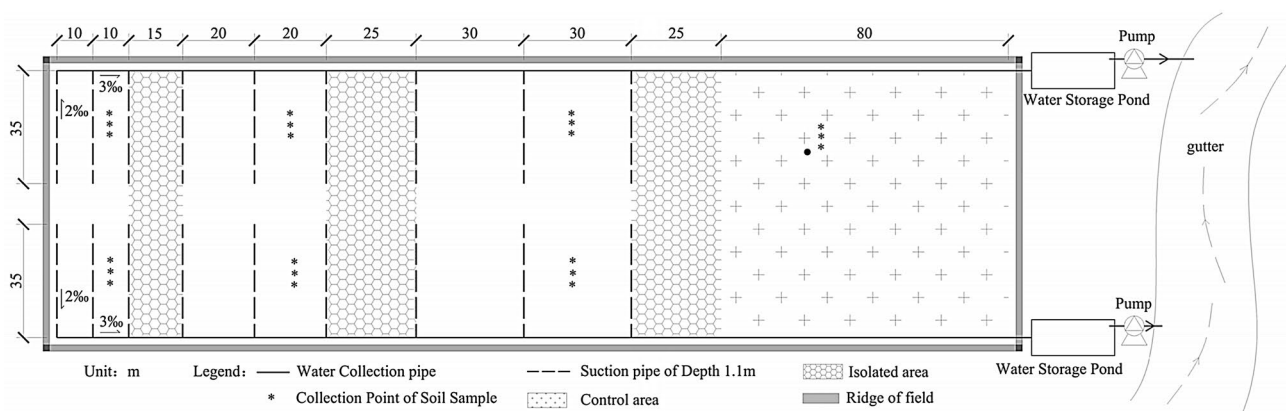
drainage pipe layout and soil sampling site are illustrated in Fig. 3.

**Agronomic management**

The test was implemented in a 1.4 ha (200 m × 70 m) cotton field with drip irrigation under film, and the cotton variety was Tamian No. 2, and the planting rate was

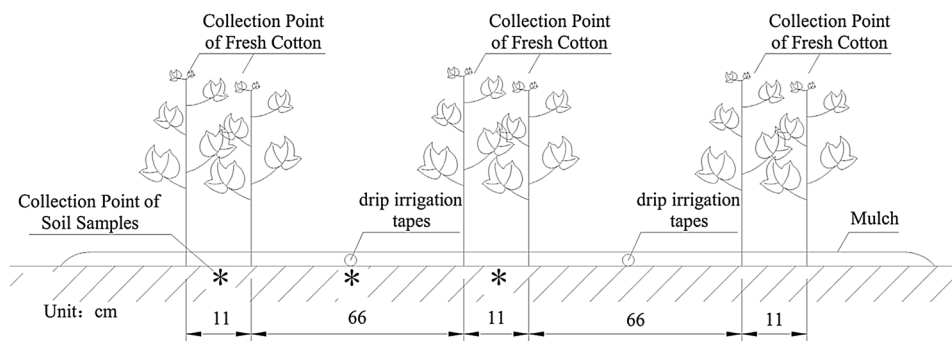
about 260,000 plants/ha. The film-mulched drip irrigation was conducted with two main tubes for six rows of cotton plants under each mulch, alternating wide and narrow spacing of 11, 66, 11, 66, and 11 cm between adjacent rows, a mean spacing of 11 cm. Labyrinth-type thin-wall drip irrigation tapes (Xinjiang Tianye Co. Ltd., China) were laid between adjacent rows. The planting layout and sampling site are illustrated in Fig. 4.

The irrigation quota for the winter-spring period in 2017 and 2018 was 225 mm. Specifically, growing-season irrigation was not provided at the seedling stage but once and twice at the budding and the flowering and boll-forming stages, respectively. The TDS content of irrigation water was 1.0 g/L. In particular, the quota for the budding stage and the flowering and boll-forming stage was 37.5 mm and 45 mm, respectively. The starting and ending dates of cotton growth stages are summarized in Table 2. Water meters and ball valves were installed on the branch pipes in each plot to measure and control the irrigation volume. Fertilizers were applied with irrigation water during the cotton-growing season, with a total application rate of 800 kg/hm<sup>2</sup> for urea and 300 kg/hm<sup>2</sup> for potassium dihydrogen phosphate. The irrigation scheme is tabulated in Table 3.



**Fig. 3** The drainage pipe layout and soil sampling point

**Fig. 4** The planting layout and sampling site



**Table 2** Start and end dates of each growth stage in 2018–2019 (from d-m to d-m)

Year	Emergence stage	Seedling stage	Squaring stage	Full-bloom stage	Full-boll stage	Harvest stage
2018	23-Apr to 30-Apr	01-May to 14-Jun	15-Jun to 07-Jul	08-Jul to 19-Jul	20-Jul to 28-Aug	29-Aug to 12-Oct
2019	27-Apr to 04-May	05-May to 17-Jun	18-Jun to 09-Jul	10-Jul to 21-Jul	22-Jul to 30-Aug	31-Aug to 15-Oct

**Table 3** irrigation scheme

Year	Irrigation date (d-m)	Irrigation quota (mm)
2018	28-Jun	37.5
	11-Jul	45
	25-Jul	45
2019	27-Jun	37.5
	13-Jul	45
	26-Jul	45

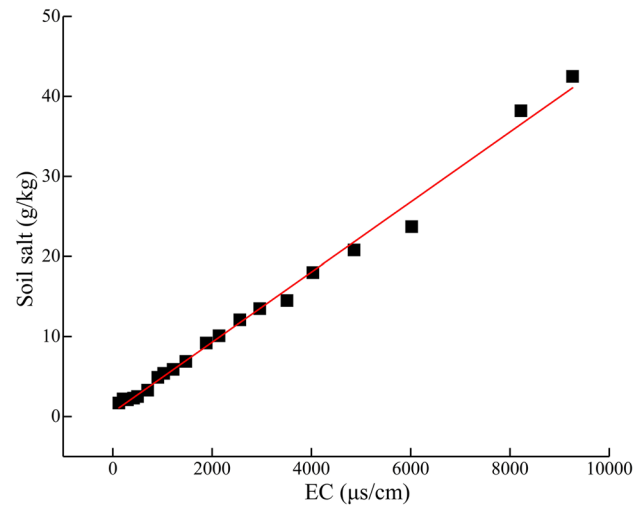
**Table 4** Soil sample collection date (d-m)

Year	Seedling stage	Squaring stage	Full-bloom stage	Full-boll stage
2018	11-Jun	26-Jun	09-Jul	23-Jul
2019	06-Jun	26-Jun	11-Jul	24-Jul

## Data collection

Soil permeability was measured using a Guelph 1800 K permeameter. Field water-holding capacity was determined in the laboratory. Soil bulk density was determined using the cutting ring method. The indoor measurement method determined the saturated soil moisture and field water-holding capacity.

Soil samples were collected at dates listed in Table 4 from seven layers (0–2 cm, 2–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm) of the soil profile (Fig. 4) at  $1/2 W$  ( $W$  is the subsurface pipe spacing, Fig. 3) between two adjacent drainage pipes, followed by the determination of soil moisture content and soil electrical conductivity. Soil moisture content on a dry-weight basis was first determined using the drying method (the electric heating constant temperature blast-drying oven was used to dry soil at a constant temperature of 105 °C) and converted to volumetric soil moisture content according to the soil bulk density (Table 1). For soil electrical conductivity measurement (DDSJ-308 A), soil samples were dried, crushed, passed through a 1-mm sieve, and soaked in water at the soil-to-water ratio (w/v) of 1:5, followed by electrical conductivity measurement of the saturated solution with an electrical conductivity meter. First, the relationship between soil salinity and soil electrical conductivity (Fig. 5) was

**Fig. 5** The relationship between soil salinity and soil electrical conductivity. The red line means fitting line of soil salinity and soil electrical conductivity

determined using the dry residue method, which was then used to estimate soil salinity. The mathematical expression of the relationship was as follows:

$$Y = 0.0044EC + 0.5438, R^2 \text{ was } 0.9924 \quad (1)$$

where  $Y$  is soil salinity (in g/kg), and  $EC$  refers to soil electrical conductivity (in  $\mu\text{s}/\text{cm}$ ).

On each sampling day (Table 4), six fresh cotton samples and several mulched soil samples were collected at the film cross-section (Fig. 4), followed by indoor measurement of dry matter weight, reproductive organ weight, chlorophyll content, and root vigor, and average the data of six cotton. The second leaves from the top were stored in the dark, followed by acetone extraction and spectrophotometric (colorimetric, UV-1200) determination of chlorophyll content. The drying method determined the dry matter weight and reproductive organ weight of cotton plants. Root vigor of cotton was determined by the tri-phenyl-tetrazolium chloride method using the tender root tips collected from the mulched soils.

Based on the emergence of seedlings in the field, five representative plots (each 2-m long and 1-m wide under the mulching film) of each treatment were selected at 20 days after sowing to calculate the seedling emergence rate. For each treatment, nine cotton plants with uniform and representative growth were selected, and their plant height and leaf area were

measured with a straightedge for each growth stage. Plots with the representative flowering status were selected at the cotton harvest stage to count the number of cotton plants and the number of bolls per plant, followed by a sampling of 20 seed cotton bolls with uniform growth to calculate the mean boll weight. The cotton in each plot was picked and weighed to calculate the actual yield of seed cotton.

The contribution of each indicator to the changes in actual yield during subsurface drainage was quantified according to the statistical significance of indirect path coefficients (indirect effect of independent variable 1 on dependent variable through independent variable 2). First, a multivariate linear regression was performed on the dependent variable with respect to the independent variables, followed by the selection of independent variables with statistical significance (statistical significance of a given independent variable was deemed at  $P < 0.1$  to fully account for the contribution of the independent variable to the dependent variable) for further analysis. Then, the correlation coefficients  $r$  between the selected independent variables were determined. Second, a logical analysis was performed to determine the indirect path coefficients of soil moisture and salt conditions with respect to actual yield, which reflect the contribution that soil moisture and salt conditions make to actual yield through affecting crop physiological growth (Du and Chen 2010). The calculation formula of indirect path coefficients was as follows:

$$P_{ij} = r_{ij} \times P_{jy} \quad (2)$$

where  $P_{ij}$  is an indirect path coefficient (a measure of the contribution that independent variable  $i$  makes to dependent  $Y$  by its effect on independent variable  $j$ ),  $r_{ij}$  is the correlation coefficient between  $i$  and  $j$ , and  $P_{jy}$  is the standardized regression coefficient of independent variable  $j$  for dependent variable  $Y$ .

## Statistical analysis

Data plotting was performed using EXCEL 2010 and Origin 2017. Data processing and analysis were performed using SPSS 23.0. Differences among the means were statistically analyzed by one-way analysis of variance followed by Duncan's new multiple range test. Unless otherwise specified, 0.05 was used as the significant level in this study.

## Results and analysis

### Soil moisture and salt distribution in the cotton field

#### Characteristics of soil moisture distribution

Water content increased with depth during each growth stage in 2018 and 2019 (Fig. 6), and the water

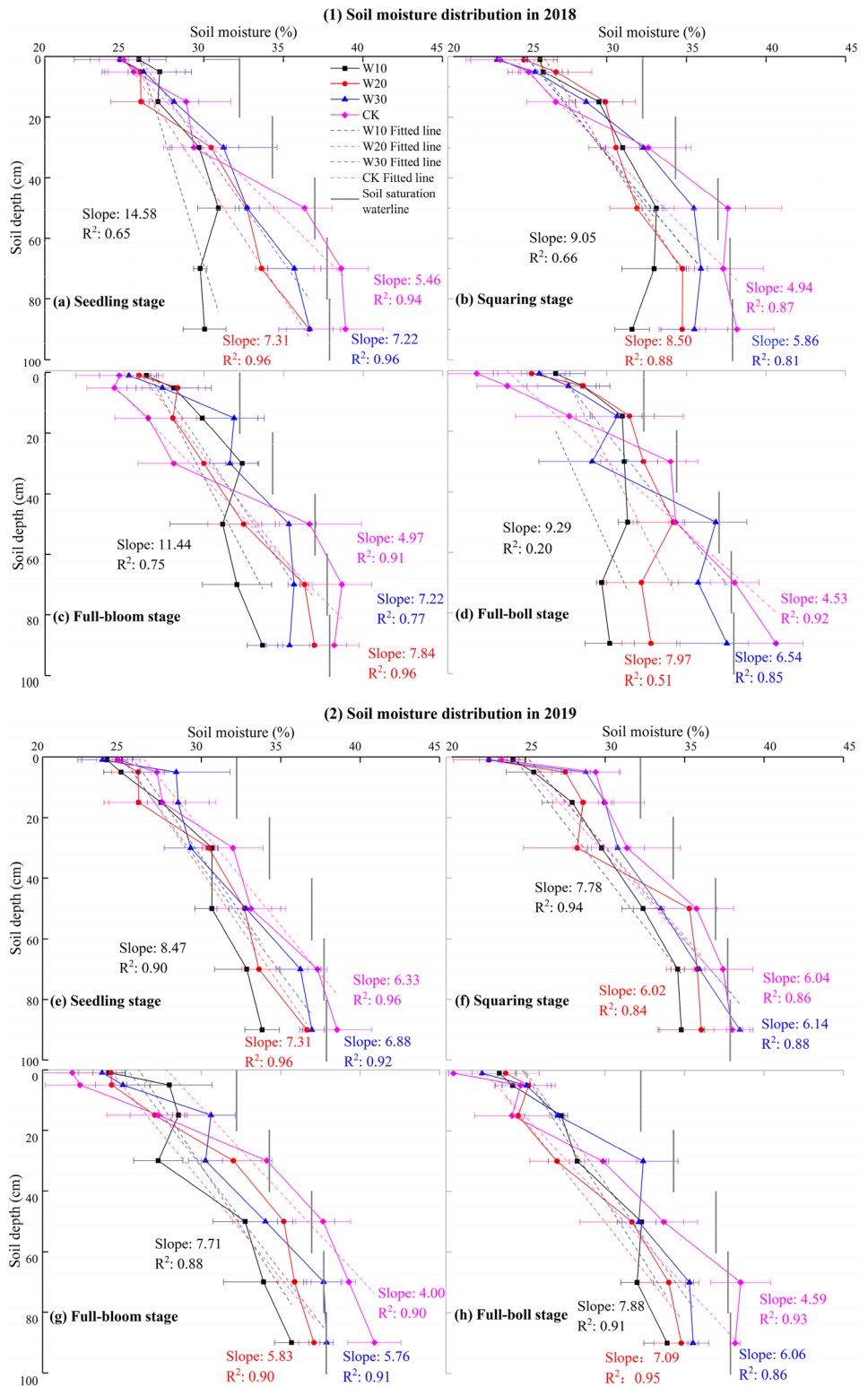
content of each soil layer was greater than 75% of the field water-holding capacity. In the case of CK treatment, the water content of the soil layer with a depth of 60–100 cm reached saturation, indicating that groundwater could not be discharged in time when there was no drainage in the test field. During the 2 years, the mean water content of the 0–100 cm soil layer under a given treatment and a given period decreased in the order of CK > W30 > W20 > W10, with significant differences ( $P < 0.05$ ), thus indicating that soil moisture content decreased with decreasing drainage pipe spacing. The mean water content of shallow soils decreased in the order of W10 > W20 > W30 > CK (0–40 cm), while the deep soils showed an opposite trend (40–100 cm). Moreover, the slope of the fitted line of soil moisture content decreased in the order of W10 > W20 > W30 > CK ( $P < 0.05$ ), indicating that as the drainage pipe spacing decreased, the difference in water content between adjacent soil layers decreased and the soil moisture distribution became increasingly uniform.

#### Characteristics of soil salt distribution

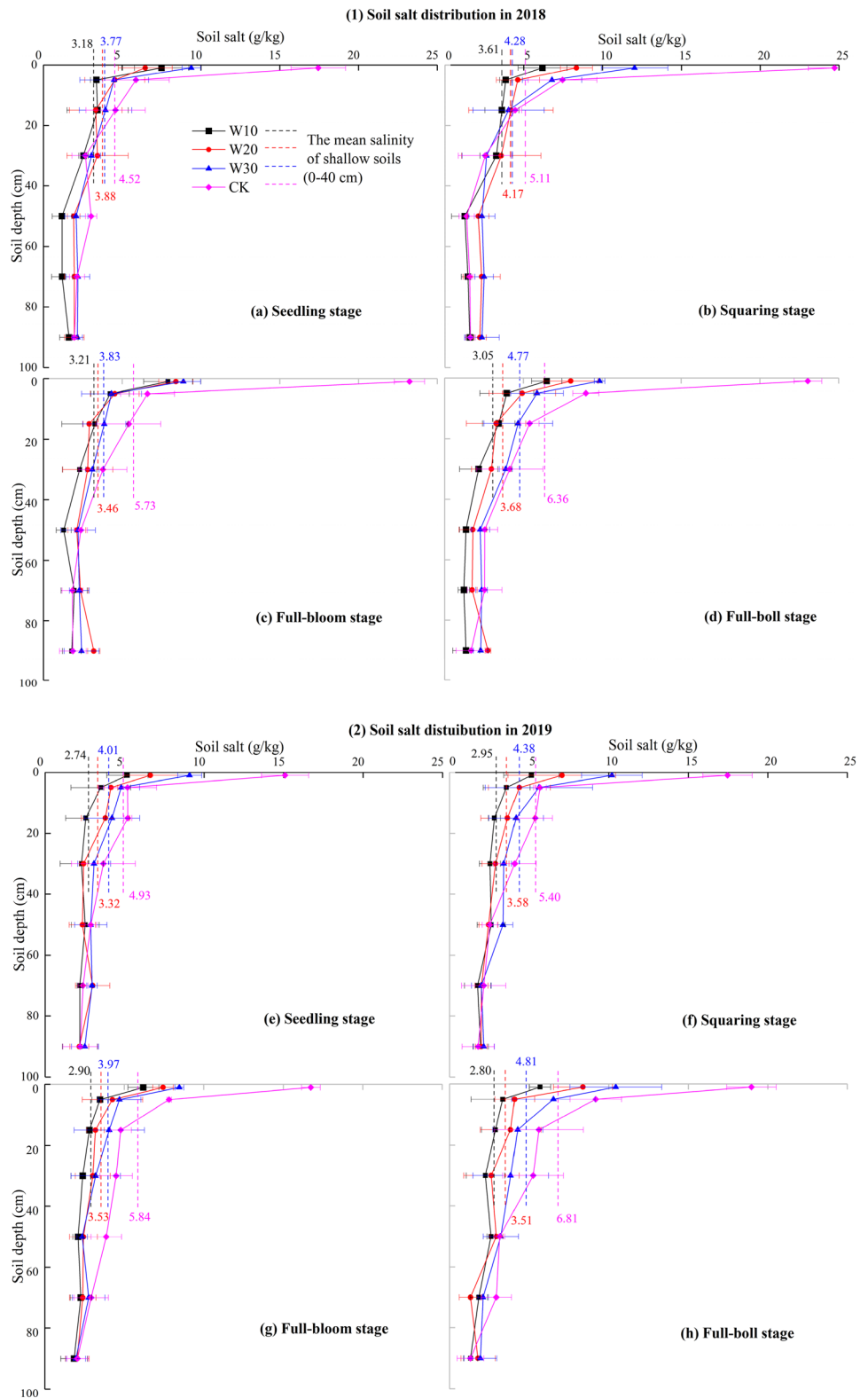
During the two years, soil salinity increased with decreasing depth and showed surface aggregation (Fig. 7). Surface soil (0–2 cm) salinity under all treatments was at least moderate ( $> 5$  g/kg), and some surface soils even reached severe salinity levels ( $> 10$  g/kg, Wang et al. 2017) under the CK treatment. The mean salinity of shallow soils (0–40 cm) decreased in the order of CK > W30 > W20 > W10, with significant differences ( $P < 0.05$ ), thus indicating that shallow soil salinity decreased with decreasing drainage pipe spacing. Compared with the seedling stages of 2018 and 2019, the shallow soil salinity in the full-boll stage of both years increased by 1.84 g/kg and 1.88 g/kg under the CK treatment, 1.00 g/kg and 0.80 g/kg under the W30 treatment, – 0.20 g/kg and 0.19 g/kg under the W20 treatment, and – 0.13 g/kg and 0.06 g/kg under the W10 treatment. These results indicated that soils had salt accumulation when there was no drainage and subsurface drainage reduced soil salt accumulation, with the reduction becoming more evident with decreasing drainage pipe spacing. With the increase in soil depth, soil salinity showed a decreasing trend and was at a low level ( $< 3$  g/kg).

Compared with that in 2018, the annual mean shallow soil salinity under the W10, W20, and W30 treatments decreased by 13%, 8%, and 9%, whereas under the CK treatment increased by 6%, respectively, indicating that salts were accumulated in soils from 2018 to 2019 when there was no drainage. However, the trend was reversed to soil desalination by subsurface drainage.

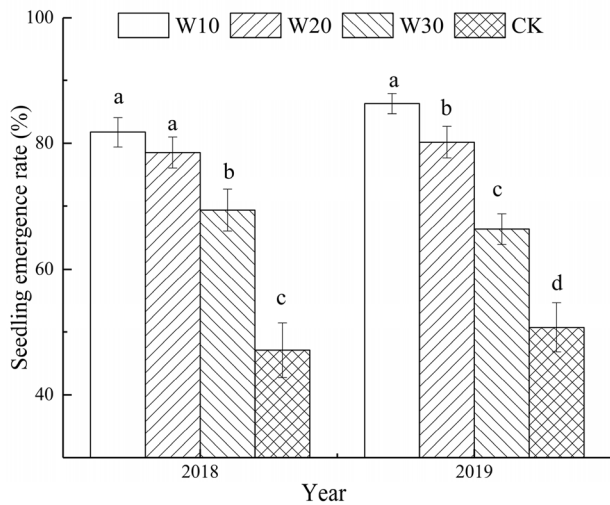
**Fig. 6** Soil moisture distribution. W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Slope and  $R^2$  mean the slope and  $R^2$  of treatments fitting lines



**Fig. 7** Soil salt distribution. W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage







**Fig. 8** Changes in cotton seedling emergence rate. W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same year

**Cotton growth characteristics**

**Changes in seedling emergence rate**

W10 treatment led to the highest seedling emergence rate of more than 80% (Fig. 8), W20 treatment led to a significantly higher seedling emergence rate than the W30 and CK treatment ( $P < 0.05$ ), and the CK treatment led to the lowest

seedling emergence rate of less than 50%. Compared with the CK treatment, the W10, W20, and W30 treatments led to a 35%, 31%, and 22% higher seedling emergence rate in 2018 and a 36%, 29%, and 16% higher seedling emergence rate in 2019, respectively, thus indicating that subsurface drainage was beneficial to cotton seedling emergence, with the beneficial effect becoming more evident with decreasing drainage pipe spacing.

**Changes in plant height and leaf area**

For each growth stage during the 2 years, both plant height and leaf area decreased in the order of  $W10 > W20 > W30 > CK$  (Table 5), and the values were significantly higher with W10 treatment than those with CK treatment ( $P < 0.05$ ). Moreover, the plant height and leaf area under W10, W20, and W30 treatments were higher in 2019 than those in 2018 ( $P < 0.05$ ). All these observations suggested that subsurface drainage promoted an increase in the morphological growth of cotton plants in a given year, and the increase became more evident as the year progressed.

**Changes in dry matter weight and reproductive organ weight**

For each growth stage during the 2 years, the dry matter weight of cotton decreased in the order of  $W10 > W20 > W30 > CK$  (Table 6), with W10 treatment resulting in significantly higher values than CK treatment ( $P < 0.05$ ). All treatments led to a significant increase in dry matter weight from 2018 to 2019 in

**Table 5** Changes in plant height and leaf area

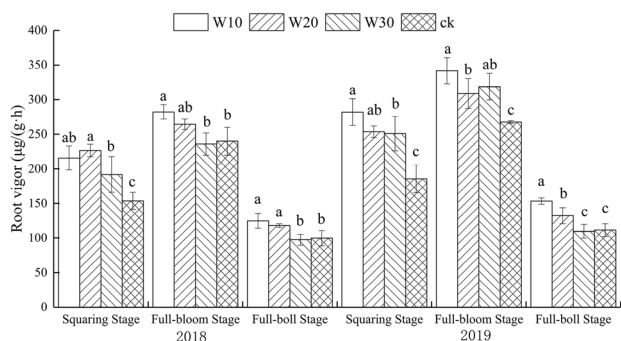
Year	Index	Treatment	Squaring stage	Full-bloom stage	Full-boll stage
2018	Height, cm	W10	27.6 ± 0.7ab	52.5 ± 1.9a	61.6 ± 2.9a
		W20	28.6 ± 2.0a	49.2 ± 2.2ab	57.9 ± 2.6ab
		W30	25.3 ± 0.9b	47.9 ± 1.9b	56.8 ± 1.6ab
		CK	22.5 ± 1.7c	44.5 ± 1.7b	50.8 ± 3.4b
	Leaf area, cm <sup>2</sup>	W10	481.4 ± 41.1a	1391.7 ± 93.4a	1827.6 ± 84.1a
		W20	509.9 ± 28.6a	1184.5 ± 47.2b	1736.1 ± 51.6a
		W30	468.3 ± 39.8a	1021.8 ± 44.5c	1525.1 ± 119.4b
		CK	373.5 ± 34.6b	953.2 ± 73.1c	1408.9 ± 103.2b
2019	Height, cm	W10	36.4 ± 1.3a	59.5 ± 1.7a	68.3 ± 0.8a
		W20	32.7 ± 0.4b	53.2 ± 0.4b	66.8 ± 1.7a
		W30	31.6 ± 1.3b	54.1 ± 1.5b	61.2 ± 1.9b
		CK	25.7 ± 1.5c	47.8 ± 2.8c	55.5 ± 1.6c
	Leaf area, cm <sup>2</sup>	W10	692.7 ± 29.2a	1666.2 ± 102.6a	2187.7 ± 89.1a
		W20	601.5 ± 32.0b	1385.0 ± 58.6b	2028.5 ± 70.1ab
		W30	565.3 ± 25.8b	1471.7 ± 105.3ab	1889.0 ± 69.4b
		CK	403.8 ± 45.7c	1007.3 ± 219.2c	1525.0 ± 133.3c

W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Values are given as mean ± SD. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same index and list

**Table 6** Changes in dry matter weight and reproductive organ weight

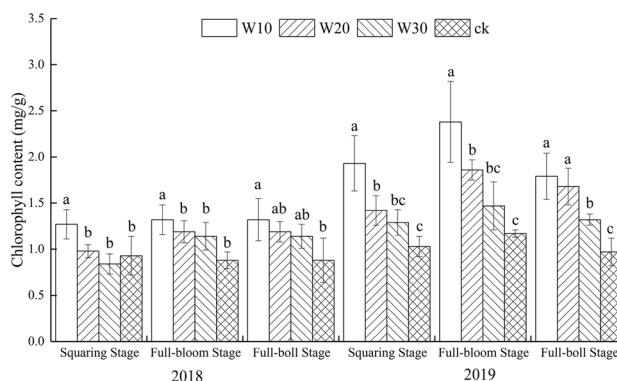
Year	Index	Treatment	Squaring stage	Full-bloom stage	Full-boll stage
2018	Dry matter weight, g	W10	13.12 ± 0.96a	52.34 ± 3.37a	62.05 ± 2.32a
		W20	12.49 ± 1.59a	37.60 ± 1.89b	60.63 ± 2.74a
		W30	12.99 ± 1.09a	34.36 ± 2.14b	54.16 ± 1.73b
		CK	9.53 ± 1.55b	30.41 ± 1.02c	48.32 ± 2.11c
	Reproductive organ weight, g	W10	1.38 ± 0.31a	15.16 ± 1.53a	29.16 ± 1.04a
		W20	1.20 ± 0.27ab	12.62 ± 0.48b	26.26 ± 0.63b
		W30	1.33 ± 0.33ab	10.43 ± 0.88c	25.39 ± 2.36bc
		CK	0.93 ± 0.13b	8.48 ± 0.83d	21.27 ± 3.48c
2019	Dry matter weight, g	W10	15.57 ± 1.48a	60.53 ± 1.82a	73.12 ± 2.25a
		W20	13.97 ± 1.08a	49.67 ± 2.68b	65.61 ± 5.26b
		W30	11.8 ± 0.39b	43.62 ± 3.37c	57.47 ± 1.88c
		CK	10.37 ± 1.04b	35.32 ± 1.93d	50.42 ± 5.17c
	Reproductive organ weight, g	W10	1.98 ± 0.25a	18.71 ± 2.01a	38.53 ± 1.04a
		W20	1.62 ± 0.41ab	14.32 ± 2.10b	31.26 ± 3.31b
		W30	1.32 ± 0.31b	12.51 ± 0.59b	30.13 ± 2.18b
		CK	1.01 ± 0.42b	9.07 ± 2.03c	24.79 ± 2.52c

W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Represents the dry matter mass and reproductive organ mass of each plant. Values are given as mean ± SD. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same index and list



**Fig. 9** Changes in cotton root vigor. W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same year

the full-bloom and full-boll stages. Reproductive organ weight decreased in the order of  $W10 > W20 > W30 > CK$  for each growth stage during the 2 years, with W10 treatment leading to significantly higher values than CK treatment ( $P < 0.05$ ) and W20 and W30 treatments leading to significantly higher values than those with CK treatment in both the full-flowering and full-boll stages ( $P < 0.05$ ). The reproductive organ weight in each growth stage under the W10 and W20 treatments significantly increased from 2018 to 2019. These observations indicated that the subsurface drainage increased the accumulation of the dry matter and reproductive organs of cotton plants in a given year. The increase became more evident as the year progressed.



**Fig. 10** Changes in cotton chlorophyll content. W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same year

## Physiological characteristics of cotton

### Changes in root vigor

For each growth stage during the 2 years, root vigor (Fig. 9) decreased in the order of  $W10 > W20 > W30 > CK$ , with W10 and W20 treatments leading to significantly higher values than those with CK treatment ( $P < 0.05$ ). The W10, W20, and W30 treatments led to an increase in annual mean root vigor by 51.51, 28.57, and 51.47  $\mu\text{g}/(\text{g h})$ , respectively, from 2018 to 2019. These observations indicated that the subsurface drainage promoted an increase in root vigor in

a given year, and the increase became more evident as the year progressed.

### Changes in chlorophyll content

For each growth stage during the 2 years, chlorophyll content (Fig. 10) decreased in the order of W10 > W20 > W30 > CK, with W10 treatment leading to significantly higher values than those with CK treatment ( $P < 0.05$ ). The W10, W20, and W30 treatments increased chlorophyll content by 43%, 41%, and 22%, respectively, from 2018 to 2019, similar to the increasing trend of root vigor. These observations indicated that the subsurface drainage promoted an increase in the chlorophyll synthesis of cotton plants, and the increase became more evident as the year progressed.

### Components of yield

In each year, the number of cotton plants decreased in the order of W10 > W20 > W30 > CK, with significant differences ( $P < 0.05$ ), which was similar to the decreasing trend of seedling emergence rate among different treatments in the same year (Table 7). The number of bolls per plant and the actual yield of seed cotton decreased in W10 > W20 > W30 > CK, and they were significantly higher under subsurface drainage than when no drainage was provided. Moreover, the number of bolls increased significantly with decreasing drainage pipe spacing. These observations indicated that the subsurface drainage significantly improved the yield components and thereby the actual yield of seed cotton. The improvement became more evident with decreasing drainage pipe spacing.

The number of cotton plants and the yield of cotton under each treatment was significantly higher in 2019 than those in 2018 by 29% and 45% ( $P < 0.05$ ).

## Discussion

In the cotton fields in arid areas where the groundwater level is shallow, due to the recharge of soil moisture by groundwater, water easily carries salt to the surface. Therefore, we performed the improvement test of subsurface drainage in the salinized cotton field with shallow groundwater levels in the oasis area of the Tarim Basin. The groundwater level of the test field was 0.6–1.0 m and adjacent to the Aksu River to the north, the Shengli Reservoir to the east, and the upstream reservoir to the west. We found that subsurface drainage led to an increase in the downward path of water, resulting in a decrease in water potential difference and a decline in upward capillary force, thereby dampening or breaking the driving force for the upward movement of salts with water. Moreover, the ground surface temperature was low, whereas the aboveground biomass was high (Tables 5 and 6) and the plant shade area was large, resulting in relatively low surface evaporation (Tanner and Jury 1976) and leading to an increase in shallow soil salinity in the order of W10 < W20 < W30 < CK (Fig. 7).

Gong et al. (2009) compared drip-irrigated cotton fields under different soil salinity conditions. They found that: (1) low-salinity areas, produced by the leaching of drip irrigation water, were mainly located in the shallow soils, and accordingly, the cotton roots were mainly distributed in shallow soils under higher salinity conditions; and (2) downward root growth of cotton was faster and reached a greater depth under lower salinity conditions. Under mulched conditions, soil evaporation was effectively suppressed, leaving plant transpiration as the main method to reduce soil moisture content. Therefore, soil salinity was high when no subsurface drainage was provided. Accordingly, roots were mainly distributed in the shallow soil layers for water absorption, resulting in low water content in shallow soils (0–30 cm) versus high water content in deep soils (30–100 cm) (Fig. 6).

**Table 7** Components of yield

Year	Treatment	The number of cotton (kn/hm <sup>2</sup> )	The number of bolls per plant ( <i>n</i> )	The weight of per bell (g)	Actual yield, kg/hm <sup>2</sup>
2018	W10	119.8 ± 2.0a	6.5 ± 0.3a	6.1 ± 0.1a	4621.3 ± 142.0a
	W20	108.3 ± 1.6b	6.3 ± 0.2ab	6.3 ± 0.5a	4338.5 ± 100.3a
	W30	100.5 ± 1.3c	6.0 ± 0.1b	5.9 ± 0.3a	3865.6 ± 162.9b
	CK	92.6 ± 1.5 d	5.1 ± 0.2 c	5.9 ± 0.4 a	2962.1 ± 409.6 c
2019	W10	138.6 ± 1.1a	6.5 ± 0.2a	5.7 ± 0.3a	5113.6 ± 131.2a
	W20	124.2 ± 2.3b	6.0 ± 0.3b	6.1 ± 0.2a	4772.7 ± 294.0a
	W30	112.5 ± 1.1c	6.3 ± 0.2ab	5.9 ± 0.3a	3977.2 ± 259.6b
	CK	88.6 ± 1.1d	5.4 ± 0.3c	6.1 ± 0.2a	3168.1 ± 280.2c

W10, W20 and W30 mean 10 m, 20 m, and 30 m spacing of the pipe, respectively. CK is control treatment without drainage. Values are given as mean ± SD. Different letters indicate values that are significantly different at the  $P < 0.05$  level for comparisons within same index and list. ‘*n*’ means number of bolls, and kn/hm<sup>2</sup> means thousand plants per hectare

Under subsurface drainage, soil salt content was low. The cotton root system could absorb and utilize the soil moisture in the 0- to 60-cm soil layer, while deep soil moisture was discharged through the buried drainage pipes (Tao et al. 2017), thereby leading to uniform water distribution in the 0- to 100-cm soil layer (Fig. 6). This phenomenon was also responsible for the significant differences among treatments in the slope of the fitted line of soil moisture content ( $P < 0.05$ ).

According to the definition of the inorganic salt concentration of soil solution ( $C$ ), the ratio of the salt content per unit volume of the soil to the water content in the same unit volume can qualitatively characterize the relationship of the  $C$  value among each treatment. For qualitative analysis, the ratio of the aforementioned shallow soil salinity (measured as g/kg, which could be converted to the dimension g/cm<sup>3</sup> using the soil bulk density) to the volumetric soil moisture content could be used to reflect  $C$ , assuming that the inorganic salt concentration of soil solution = soil salinity/volumetric soil moisture content. In this context, the lesser the soil salinity and the greater the water content, the smaller is the  $C$  value and vice versa. For each growth stage during the 2 years, shallow soil salinity under different treatments increased in the order of CK > W30 > W20 > W10, with significant differences, while shallow soil moisture content decreased in the order of W10 > W20 > W30 > CK, with significant differences. Therefore, the  $C$  value under various treatments decreased in CK > W30 > W20 > W10, showing more significant inter-treatment differences than soil salinity and soil moisture content.

Feng et al. (2019) showed that subsurface drainage improved the soil moisture and salinity conditions. In the present study, shallow soil salinity under different treatments increased in W10 < W20 < W30 < CK and soil moisture distribution was more uniform under subsurface drainage. Uniform soil moisture distribution not only is beneficial to crop root growth (water stress can negatively affect the root system) (Hu et al. 2009) but also can theoretically reduce the inorganic salt concentration of soil solution.

To describe the difference between subsurface drainage and absence of drainage, we used the average seedling emergence rate, physiological growth, and yield of subsurface drainage to compare with the mean value of absence of drainage in 2 year. The results showed that shallow soil salinity was reduced under subsurface drainage, which significantly improved the seedling emergence rate by 28%, (Fig. 8), and soil moisture was uniformly distributed. The inorganic salt concentration of soil solution ( $C$ ) was reduced, providing good soil moisture and salinity conditions for crop growth. Therefore, crop root vigor and chlorophyll content were significantly increased by 23% and 44% (Figs. 9 and 10), which was conducive to the growth of roots, stems, leaves, and buds (Foad and Ismail 2007; Yao et al. 2011;

Zhang et al. 2013a). Further, this resulted in an increase in plant height, leaf area, dry matter weight, and reproductive organ weight by 18%, 33%, 32%, and 39% (Tables 5 and 6), respectively. Consequently, the aboveground biomass increased, which led to an increase in plant shade area to reduce ground temperature effectively and surface evaporation (Tanner and Jury 1976), thereby inhibiting the upward movement of soil salts with water. In other words, an improvement in the soil environment would promote plant growth.

In contrast, good plant growth would provide positive feedback to soil improvement, thereby forming a positive feedback loop. The positive feedback loop, in this study, was ultimately manifested at the harvest stage as significantly higher numbers of cotton plants and bolls per plant and a significantly improved actual yield of seed cotton than those in the absence of drainage by 45% (Table 7). However, under the CK treatment, the inorganic concentration of soil solution ( $C$ ) was high. The water potential was low, which made the crops prone to physiological drought (Li et al. 2008), plant ion imbalance, high osmotic stress, and concomitant toxic action of single salts (Seifikalhor et al. 2019). In this condition, the plant cells are dehydrated and membrane systems are destroyed (Chaves et al. 2009), which in turn prevent the root transport, damage chloroplasts, reduce photosynthetic rate, and decrease anabolism (Maslenkova et al. 1993; Zhang et al. 2013b). As a result, the growth of different organs is strongly inhibited (e.g., leaf and root growth) (Yao et al. 2011), affecting the critical developmental stages and ultimately causing crop yield reduction (Long et al. 2019).

To clarify the relationship between soil water and salt environment and crop growth and yield under the condition of subsurface drainage spacing, a multivariate regression analysis was performed on the actual yield with respect to the indicators of soil moisture and salt conditions and crop physiological growth, leading to the identification of path coefficients. As summarized in Table 8, the independent variables with significant effects on yield were soil moisture content, soil salinity, seedling emergence rate, dry matter weight, and chlorophyll content, among which the first two were negatively correlated with yield. The absolute values of path coefficients indicated that seedling emergence rate had the largest direct contribution to the increase in yield, while soil moisture content had the smallest direct contribution. As shown by the indirect path coefficients (Table 9), soil salinity ( $i$ ) contributed the most to the increase in yield by increasing the emergence rate of cotton seedlings ( $j$ ). These observations indicated that under subsurface drainage, the seedling emergence rate of cotton had the most direct effect on cotton yield, and subsurface drainage contributed the most to the increase in cotton yield

**Table 8** Results of multiple regression analysis (stepwise regression)

Independent variables	Simple correlation coefficient with actual yield, $Y(r)$	Unstandardized regression coefficient		Standardized regression coefficient (path coefficient, direct action)	Significance
		B	Standard error		
Soil moisture, $X_1$	−0.90	−3576.89	704.60	−0.074	0.037
Soil salt, $X_2$	−0.93	−68.94	21.98	−0.070	0.088
Seedling emergence rate, $X_3$	0.98	2841.36	132.51	0.545	0.002
Dry matter weight, $X_4$	0.97	12.26	2.84	0.132	0.050
Chlorophyll content, $X_5$	0.92	531.67	56.94	0.222	0.011

The values under “significance” means the dependent variable was statistically significant for the independent variable ( $P < 0.1$ , to more comprehensively add independent variables that significant affect the dependent variable)

**Table 9** Results of multiple regression analysis (stepwise regression)

$i$	$j$		
	Seedling emergence rate, $X_3$	Dry matter weight, $X_4$	Chlorophyll content, $X_5$
Soil moisture, $X_1$	0.458	0.116	0.191
Soil salt, $X_2$	0.518	0.113	0.169

The values in table mean the correlation coefficients  $r_{ij}$  between the independent variables  $i$  and  $j$

by increasing the seedling emergence rate by reducing soil salinity.

Farmers are more concerned about cotton yield and the next-year soil arability than the indicator of crop physiological growth. For each growing season during the 2 years, the actual yield of seed cotton under different treatments decreased in the order of  $W10 > W20 > W30 > CK$  with significant differences. In addition, compared with 2018, the annual mean salinity of shallow soils in 2019 under the W10, W20, W30, and CK treatments decreased by 12.61%, 7.60%, 8.51%, and −5.76%, respectively. These observations indicated that both cotton yield and next-year soil arability could increase with decreasing drainage pipe spacing. Therefore, adopting a drainage pipe layout with small pipe spacing is favorable if economic costs are not a concern.

## Conclusion

Soil improvement under subsurface drainage was tested in 2018 and 2019 in a saline cotton field located above a shallow groundwater table in the Tarim Basin oasis and provided with film-mulched drip irrigation for years. Compared with the CK treatment, subsurface drainage reduced soil salinity, more uniform soil moisture distribution, and reduced inorganic salt concentration in shallow soil

solution. In addition to improving the soil moisture and salt conditions, subsurface drainage improved the seedling emergence rate, root vigor, and chlorophyll content of cotton plants, which in turn improved the crop height, leaf area, dry matter weight, and reproductive organ weight, ultimately leading to high cotton yield. The absolute values of path coefficients indicated that the seedling emergence rate had the largest direct contribution to the increase in yield. In contrast, soil moisture content had the smallest direct contribution, the seedling emergence rate of cotton had the greatest direct impact on cotton yield, and subsurface drainage contributed the most to the increase of cotton yield by improving the seedling emergence rate through decreasing soil salinity. The cotton yield and the next-year soil arability increased with decreasing drainage pipe spacing.

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## References

- Akhter J, Murray R, Mahmood K, Malik K, Ahmed S (2004) Improvement of degraded physical properties of a saline-sodic soil by reclamation with kallar grass (*leptochloa fusca*). *Plant Soil* 258(1):207–216
- Aragüés R, Medina ET, Zribi W, I C, álvaro-Fuentes J, Faci J, (2015) Soil salinization as a threat to the sustainability of deficit irrigation under present and expected climate change scenarios. *Irrig Sci* 33(1):67–79
- Bahceci I, Nacar AS (2009) Subsurface drainage and salt leaching in irrigated land in south-east turkey. *Irrig Drain* 58(3):346–356
- Chaves MM, Flexas J, Pinheiro C (2009) Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Annals Bot* 103(4):551–560
- Christen E, Skehan D (2001) Design and management of subsurface horizontal drainage to reduce salt loads. *J Irrig Drain Eng* 127(3):148–155
- Du J, Chen Z (2010) Path analysis using SPSS linear regression. *Bull Biol* 02:8–10 (in Chinese)

- Enciso J, Nelson S, Perea H, Uddameri V, Kannan N, Gregory A (2014) Impact of residue management and subsurface drainage on non-point source pollution in the Arroyo Colorado. *Sustain Water Qual Ecol* 3:25–32
- Evan WC, James EA, John WH (2001) Subsurface drainage design and management in irrigated areas of Australia. *Irrig Sci* 21(1):35–43
- FAO (2020) Management of salt affected soils: 'soil management' under 'FAO soils portal'. In: 'Food and Agriculture Organization' of the 'United Nations'. Rome, Available at: <http://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/salt-affected-soils/more-information-on-salt-affected-soils/en/>. (Accessed 9 April 2020)
- Fayrap A, Ko C (2012) Comparison of drainage water quality and soil salinity in irrigated areas with surface and subsurface drainage systems. *Agric Res* 1(3):280–284
- Feng G, Zhang Z, Zhang Z (2019) Evaluating the sustainable use of saline water irrigation on soil water-salt content and grain yield under subsurface drainage condition. *Sustainability* 11(22):6431
- Foad M, Ismail AM (2007) Responses of photosynthesis, chlorophyll fluorescence and ROS-scavenging systems to salt stress during seedling and reproductive stages in rice. *Ann Bot* 6:1161–1173
- Ganjugunte G, Clark J, Parajulee M, Enciso J, Kumar S (2018) Salinity management in pima cotton fields using sulfur burner. *Age* 1(1):1–10
- Gong J, Bao J, Lv N, Hou Z (2009) Effects of different soil salinity levels on the distribution of cotton root in drip irrigation under film. *Cotton Sci* 02:138–143 (in Chinese)
- Guan Z, Jia Z, Zhao Z, You Q (2019) Dynamics and distribution of soil salinity under long-term mulched drip irrigation in an arid area of northwestern china. *Water* 11(6):1225
- He Q, Li S, Hu D, Wang Y, Cong X (2020) Performance assessment of the AquaCrop model for film-mulched maize with full drip irrigation in Northwest China. *Irrig Sci* 39(2):1–16
- Hu X, Chen H, Wang J, Meng X, Chen F (2009) Effects of soil water content on cotton root growth and distribution under mulched drip irrigation. *Sci Agric Sin* 42(05):1682–1689 (in Chinese)
- Kladivko EJ, Frankenberger JR, JaynesDB, Meek DW, Jenkinson BJ, Fausey NR (2004) Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. *J Environ Qual* 33(5):1803
- Li Y, Zhang Y, Sun M, Gao B (2008) Effects of salt stress on plants and the mechanism of salt tolerance. *Chinese Agric Sci Bull* 24(001):258–265 (In Chinese)
- Long L, Yang W, Liao P, Guo Y, Kumar A, Gao W (2019) Transcriptome analysis reveals differentially expressed erf transcription factors associated with salt response in cotton. *Plant Sci* 281:72–81
- Maslenkova LT, Zanev Y, Popova LP (1993) Adaptation to salinity as monitored by psii oxygen evolving reactions in barley thylakoids. *J Plant Physiol* 142(5):629–634
- Muirhead WA, Humphreys E, Jayawardane NS, Moll JL (1996) Shallow subsurface drainage in an irrigated vertisol with a perched water table. *Agric Water Manage* 30(3):261–282
- Ning S, Zuo Q, Shi J, Wang S, Liu Z (2013) Water use efficiency and benefit for typical planting modes of drip-irrigated cotton under film in xinjiang. *Trans Chin Soc Agric Eng* 29(22):90–99 (in Chinese)
- Oquist KA, Strock JS, Mulla DJ (2007) Influence of alternative and conventional farming practices on subsurface drainage and water quality. *J Environ Qual* 36(4):1194–1204
- Rozema J, Flowers T (2008) Crops for a salinized world. *Science* 322(5907):1478–1480
- Salvati L, Ferrara C (2015) The local-scale impact of soil salinization on the socioeconomic context: an exploratory analysis in Italy. *CATENA* 127:312–322
- Sands GR, Song I, Busman LM, Hansen BJ (2008) The effects of subsurface drainage depth and intensity on nitrate loads in the northern cornbelt. *Trans ASAE* 51(3):937–946
- Seifikalhor M, Aliniaiefard S, Shomali A, Azad N, Hassani B, Lastochkina O, Li T (2019) Calcium signaling and salt tolerance are diversely entwined in plants. *Plant Signal Behav* 14(11):166455
- Shao X, Chang T, Cai F, Wang Z, Huang M (2012) Effects of subsurface drainage design on soil desalination in coastal resort of china. *J Food Agric Environ* 10(2):935–938
- Singh A (2015) Soil salinization and waterlogging: a threat to environment and agricultural sustainability. *Ecol Indic* 57:128–130
- Singh R, Helmers MJ, Qi Z (2006) Calibration and validation of DRAINMOD to design subsurface drainage systems for Iowa's tile landscapes. *Agric Water Manage* 85(3):221–232
- Sun S, Yang P, An Q, Xu R, Yao B (2016) Investigation into surface and subsurface drip irrigation for jujube trees grown in saline soil under extremely arid climate. *Eur J Hort Sci* 81(3):165–174
- Tanner CB, Jury WA (1976) Estimating evaporation and transpiration from a row crop during incomplete cover. *Agronomy J* 68(2):239–239
- Tao Y, Xu D, Chen H, Yuan H, Wang S (2017) Field and numerical experiment of an improved subsurface drainage system in Huaibei plain. *Agric Water Manage* 194:24–32
- Tian G, Gitau M, Merwade V, Arnold J, Engel B (2018) Comparison of performance of tile drainage routines in swat 2009 and 2012 in an extensively tile-drained watershed in the Midwest. *Hydrol Earth Syst Sci* 22:89–110
- Wang X, Wang H, Si Z, Gao Y, Duan A (2020a) Modelling responses of cotton growth and yield to pre-planting soil moisture with the CROPGRO-Cotton model for a mulched drip irrigation system in the tarim basin. *Agric Water Manage* 241(3):106378
- Wang Z, Jin M, Šimůnek J, Genuchten M (2014) Evaluation of mulched drip irrigation for cotton in arid Northwest China. *Irrig Sci* 32(1):15–27
- Wang Z, Heng T, Li W, Zhang J, Yang B, Jiang Y (2017) Effects of drainage pipe spacing on soil salinity leaching under drip irrigation condition. *Trans Chin Soc Agric Mach* 48(08):253–261 (in Chinese)
- Wang Z, Heng T, Li W, Zhang J, Zhangzhong L (2020b) Effects of subsurface pipe drainage on soil salinity in saline-sodic soil under mulched drip irrigation. *Irrig Drain* 69:95–106
- Yang G, Li F, Tian L, He X, Ren F (2020a) Soil physicochemical properties and cotton (*Gossypium hirsutum* L.) yield under brackish water mulched drip irrigation. *Soil Tillage Res* 199:104592
- Yang Y, Zhou X, Li D (2020b) Analysis on the effect of subsurface pipes on salt control and leaching in drip irrigation under mulch cotton field at high groundwater level in Southern Xinjiang. *Arid Zone Res* 05:1194–1204 (in Chinese)
- Yao B (2017) Study on rules and regulation of soil water-heat-salt spatiotemporal transfer under no winter and spring irrigation cotton field in southern xinjiang. China Agricultural University PhD dissertation (in Chinese)
- Yao D, Zhang X, Zhao X, Liu C, Wang C, Zhang Z, Zhang C, Qiang W, Wang Q, Yan H (2011) Transcriptome analysis reveals salt-stress-regulated biological processes and key pathways in roots of cotton (*Gossypium hirsutum* L.). *Genomics* 98(1):47–55
- Yu S, Liu J, Eneji AE, Han L, Tan L, Liu H (2016) Dynamics of soil water and salinity under subsurface drainage of a coastal area with high groundwater table in spring and rainy season. *Irrig Drain* 65(3):360–370
- Zahedifar M, Moosavi AA (2019) Assessing cadmium availability of contaminated saline- sodic soils as influenced by biochar

using the adsorption isotherm models. *Arch Agron Soil Sci* 66(12):1735–1752

Zhang L, Chen B, Zhang G, Li J, Wang Y, Meng Y, Zhou Z (2013a) Effect of soil salinity, soil drought, and their combined action on the biochemical characteristics of cotton roots. *Acta Physiol Plant* 35(11):3167–3179

Zhang L, Zhang G, Wang Y, Zhou Z, Meng Y, Chen B (2013b) Effect of soil salinity on physiological characteristics of functional leaves of cotton plants. *J Plant Res* 126(2):293–304

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