Irrigation Science (2023) 41:687–699
https://doi.org/10.1007/s00271-022-00827-6

ORIGINAL PAPER

Eight-year comparison of agroeconomic benefits of open ditch and subsurface pipe drainage in mulched drip irrigated saline–sodic farmland

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Received: 25 August 2021 / Accepted: 7 September 2022 / Published online: 23 September 2022

Abstract
Because of the presence of shallow water tables and consequent secondary salinization in irrigated areas of Xinjiang China, there is an urgent need for installation of drainage systems to control the salinity levels in the crop rootzone. The goal of this study was to compare the midterm effects of the open ditch (depth of 2.2 m) and subsurface pipe (depth of 2.2 m) drainages on soil salinity, drainage, groundwater, cotton biomass, yield, and economic benefits while using drip irrigation under mulch (plastic film). We conducted a field experiment for eight consecutive years (2012–2019) in Shawan County of Xinjiang, China. Our experimental results indicated that open ditch and subsurface pipe drainages each reduced total soil salinity, improved saline–sodic soils, and controlled groundwater level, which caused a significant increase in the cotton biomass and yield. The open ditch drainage treatment (ODDA) represented a better desalination effect than the subsurface pipe drainage treatment (SPDA) at 73% and 81%, respectively. The electrical conductivity and pH of ODDA and SPDA water samples decreased as the soil salinities decreased over time. We used the farmland conditions from 2012 as the baseline for our experiment and evaluated how these baseline conditions changed over time in response to these treatments. Compared to this baseline, the cotton yield of ODDA and SPDA treated farmland increased by 18.30 times and 19.96 times in 2019, respectively. The investment payback periods for ODDA and SPDA treatments were 7.59 and 6.34 years, respectively, and their returns on investment were 12% and 30%, respectively. The midterm economic benefits of subsurface pipe drainage were more prominent than those of open ditch drainage. These results provide a reference for improving, developing, and utilizing soil saline–sodic land, and the sustainable development of agriculture in arid areas.

Introduction

With a population of 1.4 billion, the development of its national economy, and the acceleration of industrialization, the amount of cultivated land occupied in China has increased in recent years. China's per capita arable land resources are lacking, but there is significant potential for expanding the arable land through the development of saline–sodic land (Yun and Chen 2020). Controlling the secondary salinization of cultivated land while developing and using saline–sodic land is an urgent issue for China's agricultural production. Located in the hinterland of Eurasia,

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Xinjiang is the driest region in China with the greatest distribution of saline lands, resulting from secondary salinization, accounting for 31% of the total area of Xinjiang and 22% of the total area of China's saline–sodic soil regions (Liu and Zhang 2017).

In Xinjiang, a common method of irrigation is known as drip irrigation under mulch where the mulch is a 0.015 mm thick plastic sheet that covers the drip tubing and extends over the entire area that is cropped. This reduces water lost to direct evaporation to the air and increases the soil temperature near the soil surface (Dong et al. 2009; Ning et al. 2013). By the end of 2020, Xinjiang's water-saving irrigation area reached 2.97×10^6 ha (Hectare), accounting for 61.75% of Xinjiang's total irrigation area of 4.81×10^6 ha, including 2.45×10^6 ha of drip irrigation under mulch, accounting for 50.94% of Xinjiang's total irrigation area, driving Xinjiang to become the world's largest area of large-scale drip irrigation under mulch (Bureau of Statistics of Xinjiang Uygur Autonomous Region 2020). After the large-scale application of drip irrigation under mulch technology in Xinjiang, the original drainage canals were gradually abandoned resulting in salt accumulation within the crop rootzone because of inadequate natural drainage (Tian et al. 2018). To alleviate the agro-ecological problems caused by midterm drip irrigation under mulch, such as increased groundwater level and secondary salinization of the soil (Meng et al. 2017; Wang et al. 2014), salt leaching technology that combines irrigation and drainage, as done worldwide (Oster and Jayawardane 1998; Wang et al. 1993; Szabolcs 1986, 1994; Hilgard 1886) needs to occur.

At present, the most commonly used drip irrigation and leaching-supported drainage technologies are open ditch and subsurface pipe drainage (Liu et al. 2014, 2021). The open ditch and subsurface pipe drainages and the desalination technologies are based on the principle that "salt comes and goes with water". If there is an impervious layer deep in the soil, when precipitation or irrigation occurs, the salt will migrate to the open ditch, or subsurface pipe, with the water. The soil is then discharged through this open ditch or subsurface pipe to achieve the effect of salt drenching and salt washing. At the same time, the groundwater level is maintained at a critical depth, inhibits the upward movement of groundwater and reducing secondary salinization of the soil, thus achieving the control of salinity levels in the rootzone (Ritzema et al. 2006; Yu et al. 2016). Researchers have conducted a series of field and quantitative estimation experiments to measure how applying these different drainage techniques could reduce soil salinity, control groundwater level, increase crop yield, and improve economic benefits (He et al. 2016; Li et al. 2019; Chen 2016). These studies have found that both open ditch and subsurface pipe drainage effectively reduce soil salinity. The salinity of soil layers decreased significantly, and in these studies, the closer the soil was to the open ditch or subsurface pipe, the greater the desalination rate (He et al. 2016; Ritzema et al.2008; Wang et al. 2020). Open ditch and subsurface pipe drainage have significantly increased the control of groundwater levels during crop growth and soil thawing periods, reduced the groundwater level over time, controlled waterlogging disasters and reduced the time that mechanical harvesting could not occur due to rainfall (Chen et al. 2018; Yao et al. 2005; Yu et al. 2016). Drip irrigation and drainage systems can also accelerate dry matter production and mineral nutrient absorption resulting in increased crop yields (Hou et al. 2016; Li et al. 2019; Sallam 2017). Additionally, comparing engineering construction costs, operation cycle and maintenance management, and the technical characteristics of these drainage methods indicated that subsurface pipe drainage can save 10–15% of the land area and improve land utilization rates and economic benefits when compared to open ditch drainage (Chen 2016; Yao et al. 2005).

Much of these previous works were quantitative assessments conducted of short-term effects (≤ 2 years) and were limited to a specific aspect (soil conditions, crop characteristics, or economic benefit). For Xinjiang, there are no published results of midterm studies on the impacts of different drainage methods on soil salinity, groundwater, crop yield, and economic benefit. Therefore, we conducted an 8-year field experiment to determine the midterm impacts of subsurface pipe and open ditch drainage on salinity levels in the soil, drainage water, and groundwater. The impacts on crop yields and the costs of installation and maintenance were used to assess the economic benefits of the two drainage systems. This analysis fills the gaps in the literature and provides a theoretical basis for the improvement, development, and utilization of soil saline–sodic land and the sustainable development of agriculture in arid areas.

Materials and methods

Description of the study area

The experimental site was located at the Xiayedi Irrigation Area (44°41′N, 85°39′E) (Fig. 1) in the suburbs of Shawan in northern Xinjiang, an autonomous region in north-western China, and belongs to the temperate continental climate zone. The annual average sunshine was 2743 h. The temperature ranged from − 31.6 to 42.9 ℃, and the average annual precipitation was 123 mm (Fig. 2). The main physical properties of the 0–200 cm soil layer in the experimental area are shown in Table 1. The groundwater level in the test area was relatively shallow (1.5–2.1 m) in spring and summer, and relatively low (2.2–3.5 m) in autumn and winter.

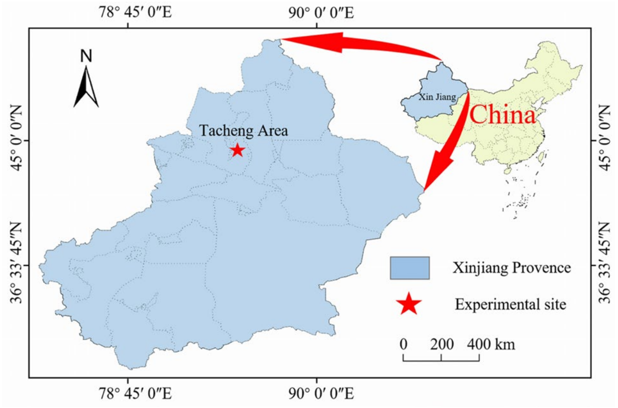


Fig. 1 The location of experimental site

Experimental design and treatments

We conducted this research in six experimental plots (each 144 × 80 m). Adjacent plots were separated by 30 m to eliminate lateral soil water and salt seepage (Fig. 3a). All treatments consisted of drip irrigation under mulch using two different drainage methods (open ditch drainage: ODDA; subsurface pipe drainage: SPDA). In October 2011, open ditch and subsurface pipe drainage were constructed in the study area. The distance between the subsurface pipes, which were a spacing of 48 m, a depth of 2.2 m, and a 3‰ design slope. In contrast, the spacing, depth and slope of the open ditch were the same as those of the subsurface pipe. The width of each open ditch was 10 m at the top and 0.7 m at the bottom. And the side slope of the open ditch drainage was 1:2.11. The pipe was a perforated corrugated pipe (Polyvinyl chloride) (diameter = 10 cm) encircled by a 20 cm-thick sand filter (Zibo Shandong Province, China), was laid by digging trenches with an excavator (Fig. 3b and Fig. 3c). The study area was close to the west bank canal of the Manas River, and a blocking ditch was constructed between the study area and the west bank canal to leave the groundwater at its normal level and slow the impact of the canal on the groundwater level in the test area.

The Chuangza No. 100 cotton variety, widely grown in the local area, was used for all of our experiments. The cotton was planted in mid-to-early April and harvested in mid-to-late September. A ‘one mulch, two drip pipes, and six crop rows’ pattern (Fig. 4) was used, which is the main cultivation pattern used by the local cotton

Fig. 2 Precipitation and temperature from 2012 to 2019

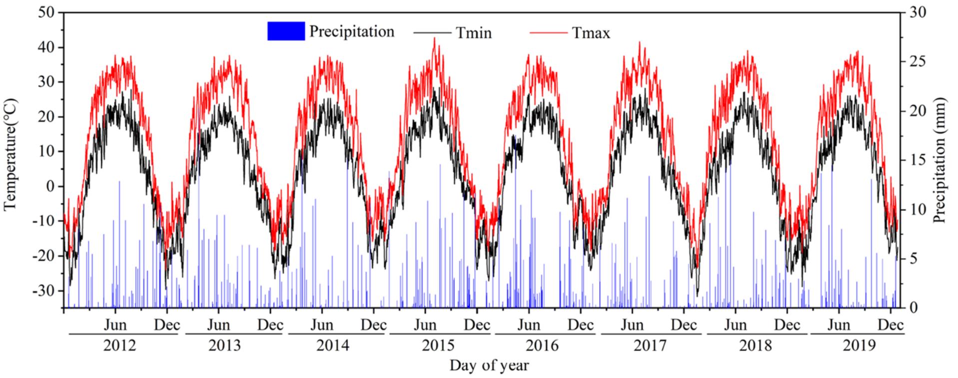


Table 1 Main physical properties of the soil in the study area

Treatments	Soil depth (cm)	Soil texture	Particle mass fraction (%)			Bulk density (g·cm^{-3})	SWC (%)	FWHC (%)	PWP (%)	EC (mS·cm^{-1})
			Sand	Silt	Clay					
ODDA	0–50	Sandy loam	61.47	34.48	4.05	1.38	41.14	25.18	13.35	6.24
	50–100	Sandy loam	68.23	29.35	2.42	1.39	42.66	25.45	14.15	4.75
	100–150	Sandy loam	71.57	23.48	4.95	1.42	43.15	26.14	14.83	4.11
	150–200	Sandy loam	66.24	30.55	3.21	1.43	45.31	26.48	15.17	3.51
SPDA	0–50	Sandy loam	62.25	34.87	3.88	1.38	42.34	25.04	13.41	6.43
	50–100	Sandy loam	67.11	30.14	2.75	1.39	43.14	25.49	14.19	4.82
	100–150	Sandy loam	70.76	24.51	4.73	1.41	44.25	26.33	14.85	4.23
	150–200	Sandy loam	65.45	31.23	3.32	1.42	46.18	26.54	15.14	3.59

ODDA open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment; *SWC* saturated water content; *FWHC* field water holding capacity; *PWP* permanent wilting point; *EC* electrical conductivity crop management. The thickness of the mulch film was 0.015 mm and the width was 2.02 m. We used a single-wing labyrinth drip irrigation belt (Xinjiang Tianye Water-saving Irrigation Co. Ltd. Shihezi, China) for irrigating the plots. The diameter of the drip irrigation belt was 16 mm, the wall thickness was 0.2 mm, the distance between drippers was 30 cm, and the flow rate was 3.2 L h^{-1}. The drip irrigation water source was the canal on the west bank of the Manas River, which had a salinity of 0.6 mS cm^{-1} and 7.82 pH. Experienced local farmers suggested an irrigation cycle of 7–10 d, with ten total irrigations, making the total irrigation quota 720 mm (Table 2). We installed a water meter and ball valve at each plot to control their irrigation quotas. The operation pressure, provided by a submerged pump, was 0.09 MPa and we assumed that an equal amount of water was applied to each plot; and that the crop rows and drip tapes were parallel to the drainage pipes and ditches.

According to the local recommended fertilization level and method, 30% nitrogen fertilizer was used as base fertilizer and 70% as topdressing. All phosphorus, potassium, and micro-fertilizers were basally applied in mid-to-early April (N 240 kg ha^{-1}, P_2O_5 105 kg ha^{-1}, K_2O 75 kg ha^{-1}, $FeSO_4$ 19.5 kg ha^{-1}, $MnSO_4$ 10.5 kg ha^{-1}, $ZnSO_4$ 10.5 kg ha^{-1}). Subsequently, the farm was deep plowed, and sowed the next day. The nitrogen, phosphorus, and potassium fertilizers were urea (46% N), calcium phosphate (P_2O_5 46%), and potassium sulfate (K_2O 51%), respectively. During the main cotton growth period, the nitrogen fertilizer was dissolved into a concentrated solution through the fertilization tank and applied five times in droplets with irrigation water: 10.5% at bud stage, 24.5% at first flowering stage,

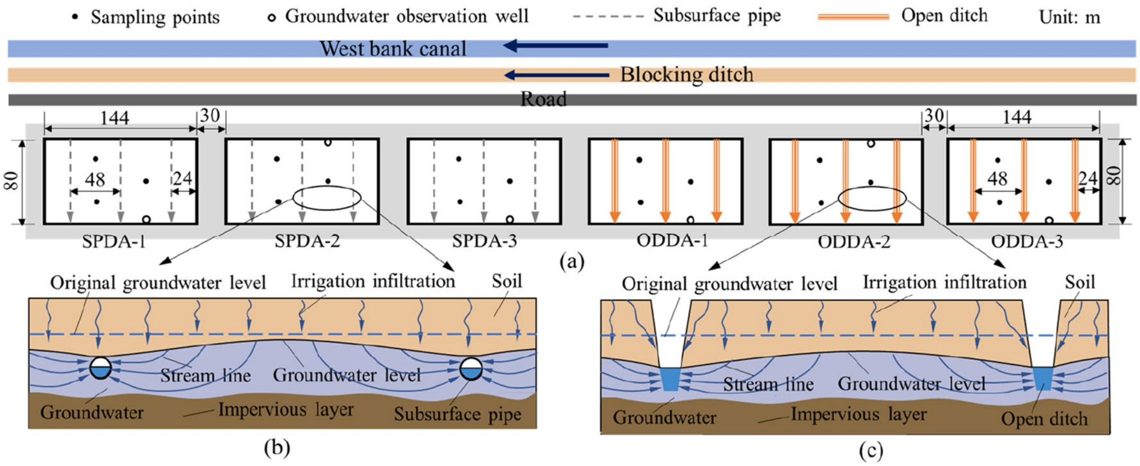


Fig. 3 The layout of the experimental plots, the schematic diagram of vertical section between two adjacent subsurface pipes (**b**) or open ditches (**c**). 1 The dimensions of (**b**) and (**c**) were not in scale. 2 ODDA, open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment

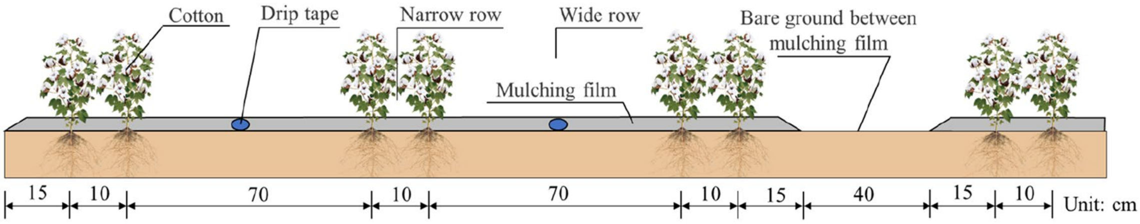


Fig. 4 The planting pattern of cropping system mulched drip irrigation

Table 2 Irrigation schedule implemented during the cotton growth period

Irrigation date	Late April	Early May	Early June	Mid-June	Late June	Early July	Mid-July	Late July	Mid-August	Late August
Irrigation quota (mm)	180	60	60	60	60	60	60	60	60	60

Both drainage treatments had the same water quantities for all years

17.5% at blooming boll stage, 14% at full boll stage, and 3.5% at boll opening stage.

Data collection and measurement

Data collection

During the irrigation cycle and cotton growth period, soil samples were collected at the seedling stage in mid-May, flowering stage in mid-July, and cotton bowl opening stage in mid-September. At three sites in each replicate (Fig. 3a), we collect soil samples to a depth of 200 cm at a distance of 24 m from the open ditches and subsurface drainage pipes. The samples were divided into ten depths: 0–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, and 180–200 cm. The positioning of the handheld GPS device ensures that the sampling accuracy was within 1 m.

During the cotton-growing period (between months 4 and 9 each year), ODDA and SPDA drainage water samples were collected on the first of each month. Forty water samples were collected from 2012 to 2019. We also collected water samples from groundwater observation wells.

Electrical conductivity and pH

The soil samples were air dried and pulverized until they could pass through a 2 mm sieve. Then, dry soil and distilled water were mixed at a ratio of 1:5 (by weight). The electrical conductivity (EC, mS cm^{-1}) of soil extract and drainage water samples were measured with a DDS-11A digital conductivity meter (Shanghai INESA Scientific Instruments Co. Ltd. Shanghai, China). A Hach LA-pH10 laboratory pH meter (Shanghai Shilu Instrument Co. Ltd) was used to measure the pH of the drainage water samples.

Biomass and yield

At the harvest stage, three cotton plants with uniform growth were randomly selected from each plot of ODDA and SPDA, respectively. The roots, stems, and leaves were separated, washed with deionized water, put in an oven at 105 °C for 0.5 h, and then dried at 70 °C to a constant weight. After drying, they were cooled and weighed.

Three 1×2.4 m plant samples from ODDA and SPDA were randomly selected and the seed cotton yields were weighed. The measured yield factors were 100-boll weight, plant number, and effective boll number per plant.

Economic benefit analysis

For the open ditch and subsurface drainage methods, the input costs included three factors: installation of the drainage systems, crop production, and operating costs (Li et al. 2016). The drainage system costs included purchase and installation. The open ditch drainage cost \$667 USD ha^{-1} as compared to \$1335 USD ha^{-1} for pipe drainage. These costs were amortized over eight years. Crop production costs included land lease, mulching film, drip irrigation tape, cotton seeds, chemical fertilizers, pesticides, irrigation water, machinery, and labor. Annual operating costs included dredging fees and loss of income from the open ditch land. Annual dredging fees for the open ditch were calculated according to the actual occurrence each year, and the land occupation loss fee was 17% (based on the calculation) of the seed cotton income (open ditches covered an area of 17%). Income was the yield of seed cotton multiplied by the purchase price of that year. The unit price of materials involved in the crop production and operating costs (\$ ha^{-1}) was determined by the current market prices from 2012 to 2019 (Liang et al. 2020).

Net present value (NPV) and return on investment (ROI) were calculated as:

$$\mathrm{NPV} = \sum_{t=0}^{n} (B_t - \mathrm{C}_t)(1 + i)^{-t}, \tag{1}$$

$$\mathrm{ROI} = \frac{T_O - T_i}{T_i}, \tag{2}$$

where $B_t - \mathrm{C}_t$ is the net benefit in year t (\$ ha^{-1}); i is the benchmark discount rate, 8%; T_o is the total output value (\$ ha^{-1}); T_i is the total input value (\$ ha^{-1}); ROI is the rate of return on investment (%). The depreciable life is 8 years and there is no salvage value.

Statistical analysis

All data are shown as the mean of multiple data points from three plots in the same treatment. The figures were created using Origin 2021 (OriginLab, Northampton, Massachusetts, USA.). Variance analysis was carried out using the SPSS 26.0 package (SPSS Inc. Chicago, USA). The Least Significant Difference (LSD) method was used to test the significance of the difference between treatments ($P < 0.05$).

Results

Changes in soil salinity in response to drainage treatment

Before sowing in 2012, the surface soil salt content was high, however, the salt content in deep soil was low (Table 1). The salt mainly accumulated in the surface layer (0–50 cm); the salt content in the upper layer (0–80 cm) was significantly different from that in the lower layer (100–200 cm). After eight years of using these different drainage treatments, the soil salinity was redistributed and significantly reduced (Fig. 5). The soil salinity of each soil layer decreased vertically over time, the overall soil salinity moved to and accumulated in the lower layer and the depth of accumulation was related to drainage treatment duration. In 2019, the upper and lower soil salt salinity distributions in ODDA and SPDA were relatively uniform, with a stable range of change. The salinity of ODDA decreased from 3.39–6.72 to 0.50–1.09 mS cm^{-1}, which was 81% lower than the initial salinity. The salinity of SPDA decreased from 3.44–7.02 to 0.99–1.78 mS cm^{-1}, which was 73% lower than the initial salinity.

Desalination varied by depth and time during the eight years. During the first year, the following occurred: 1. salt levels for ODDA were reduced by 12% in the 0–100 cm depth interval whereas salt levels increased by the same percentage in the 100–200 cm depth interval (Fig. 6), and 2. Similar changes occurred for SPDA. Desalination in 0–80 cm decreased annually while in the at depths below 80 cm, salinity first increased then decreased. After 2 years, desalination occurred at all depths for both drainage treatments. After 8 years, compared with the initial salinity, salinity levels above 80 cm for ODDA and SPDA were reduced by 88% and 81%, respectively, with corresponding salinities of 1.0 and 1.3 mS cm^{-1}. And, after eight years, salinities levels below depths of 100 cm were reduced by 73% for the ODDA treatment and 66% for the SPDA treatment. These results show that both ODDA and SPDA effectively reduced salinity with the ODDA treatment resulting in the greatest reduction.

Changes in the salinity and pH of the drainage water in response to ODDA and SPDA

From 2012 to 2019, the salinity of drainage water (Fig. 7) generated by the ODDA treatment decreased from 90 to 30 mS cm^{-1}. For the SPDA treatment, the salinity decreased from 120 to 50 mS cm^{-1} in 2018 and then increased to 60 mS cm^{-1} in 2019. During each growing season, the salinity of the drainage water from both treatments increased than decreased reaching peak values in June. Generally, the drainage water pH increased with salinity (Fig. 8). Consequently, the changes in pH with time were like those for drainage water salinity. As was the case for soil salinity, the salinity and pH of the drainage water generated by SPDA were significantly greater than those the drainage water generated by ODDA.

Seasonal changes in groundwater level and drainage

Annually, in April because of snow melt and the thaw of soil water, groundwater levels rose (Fig. 9), and drainage started. Drainage continued through the crop season due to irrigation. In the fall after irrigation ended and the cotton was harvested, groundwater levels declined, and drainage stopped. The highest groundwater levels occurred in August. The monthly fluctuations in groundwater level for

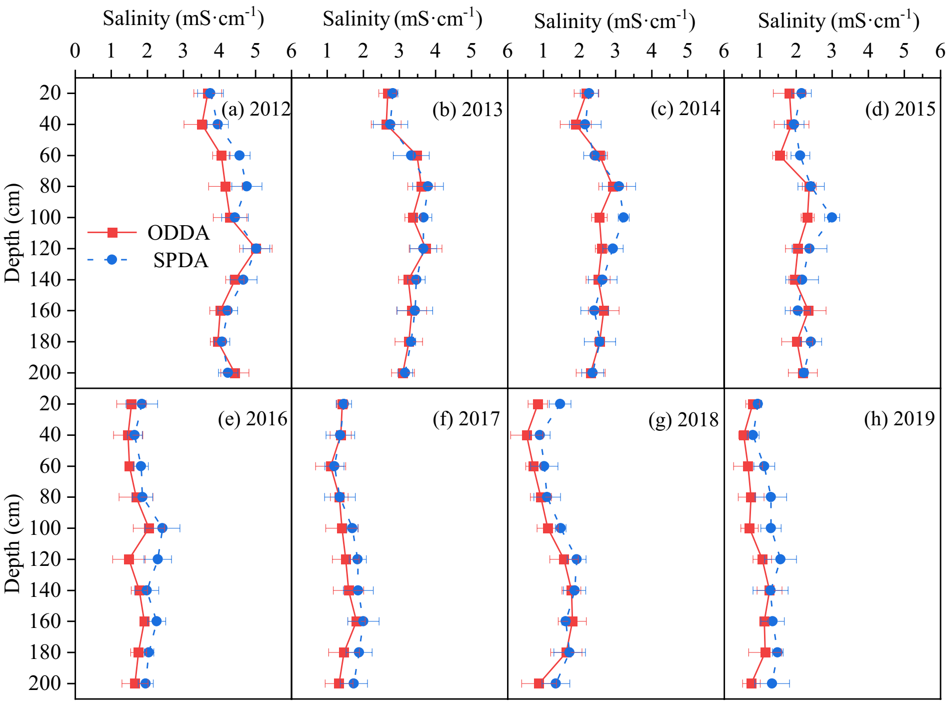


Fig. 5 Distribution of soil salinity using different drainage measures in cotton fields between 2012 and 2019. [1]Data were mean data (±SD) for seedlings, flowering, and cotton bowl opening from 0 to 200 cm soil depths. [2]ODDA, open ditch drainage treatment; SPDA, subsurface pipe drainage treatment

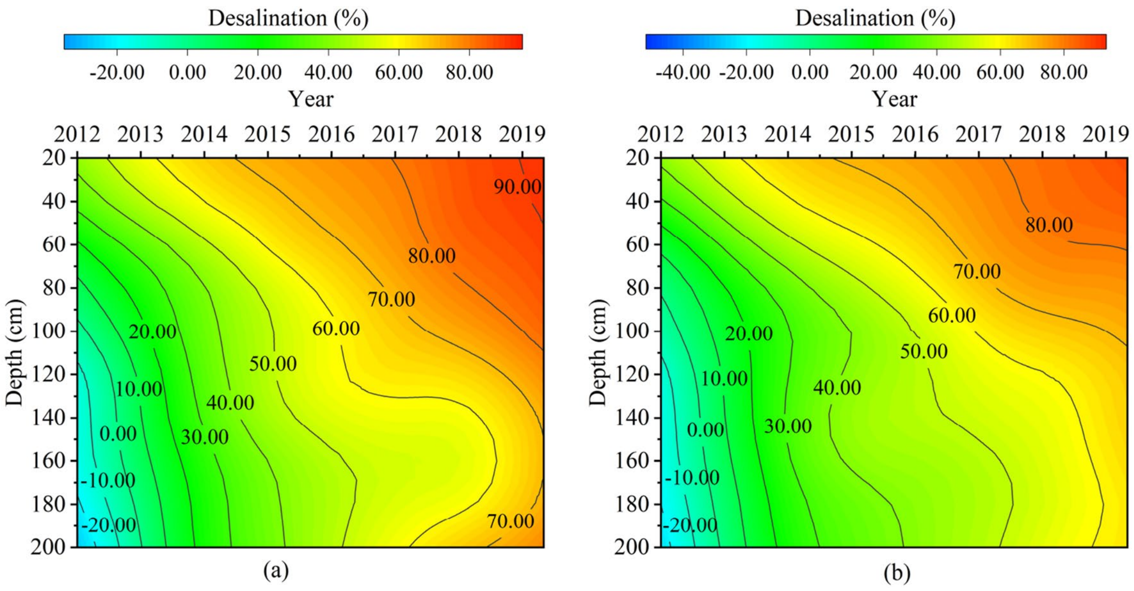


Fig. 6 Effect of time on the extent of desalination (in percent) relative to soil salinity levels at the start of the experiment in 2012. ^{1}**a** open ditch drainage treatment (ODDA), ^{2}**b** subsurface pipe drainage treatment (SPDA)

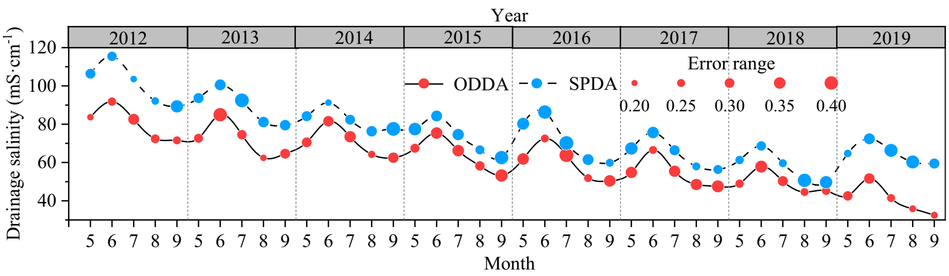


Fig. 7 Monthly changes in electrical conductivity (EC) of drainage water from 2012 to 2019 during the growing season of cotton. ^{1}*ODDA* open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment. ^{2}Error range from 0.2 to 0.4 mS cm^{-1}

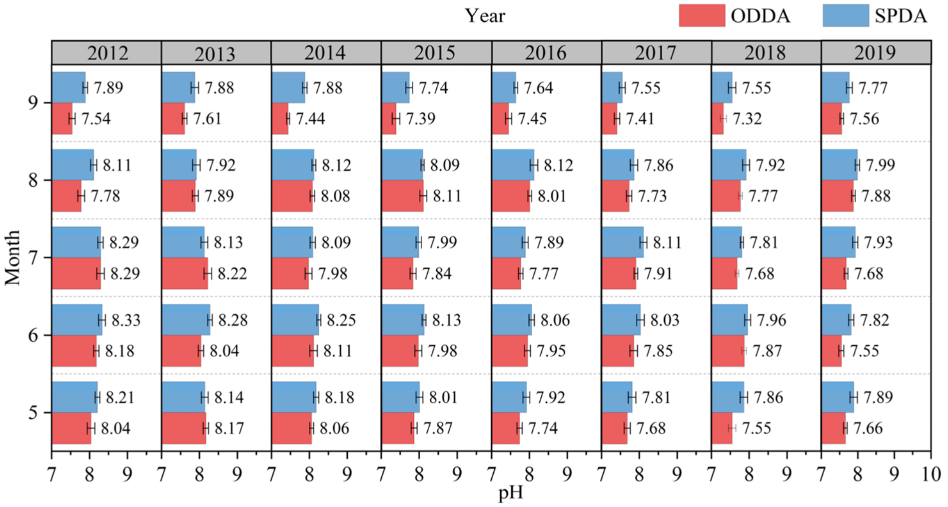


Fig. 8 The change of drainage water pH in samples from 2012 to 2019. ^{1}Data (average ± SD) were collected each month during the cotton-growing period. ^{2}*ODDA* open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment

both irrigation treatments during each year were similar. During the eight years, the annual extent of the changes in groundwater table depth was similar for both irrigation treatments. However, starting in 2014, the depth of the groundwater table for the ODDA treatment was always lower than that for the SPDA treatment. When comparing these two types of designs used in this study, these results show that both drainage treatments controlled the

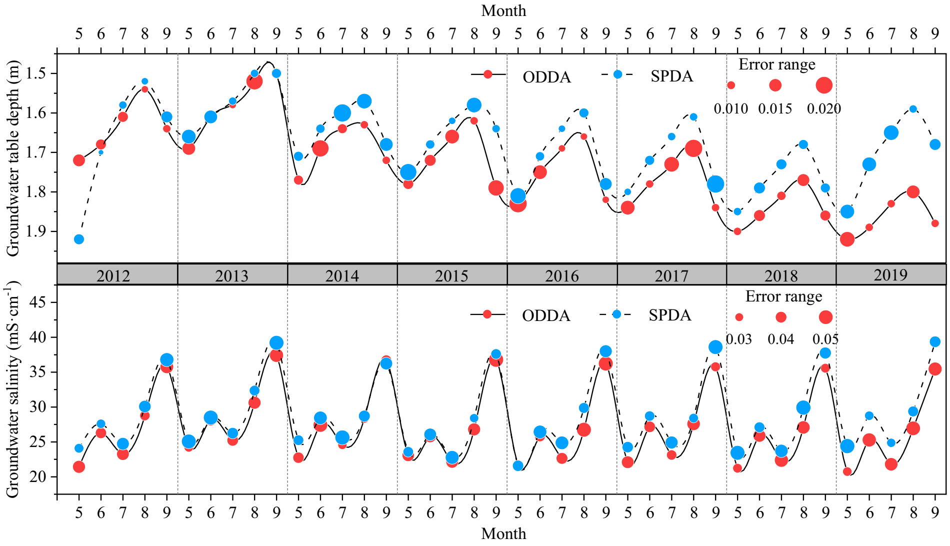


Fig. 9 The dynamic changes in groundwater table depth and salinity between 2012 and 2019. ^{1}*ODDA* open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment. ^{2}The groundwater table depth error ranges from 0.010 to 0.020 m; the groundwater salinity error ranges from 0.02 to 0.05 mS cm^{-1}

groundwater depth, but the control was best for the ODDA treatment.

During the cotton growth period, the groundwater salinity increased, then decreased before it reached its highest value in September (Fig. 9). The groundwater salinity of ODDA and SPDA varied from 20.75–37.4 to 21.55–39.35 mS cm^{-1}, respectively. The groundwater salinity fluctuated slightly in the same month each year, but there were no significant annual differences. The results showed that the ODDA groundwater salinity reduction effect was better than that of SPDA.

Drainage affects cotton dry matter

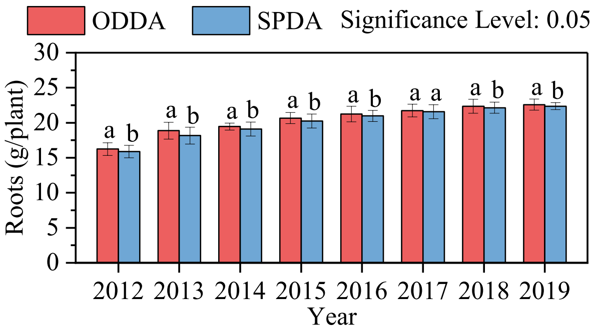
Drainage treatments increased the annual dry matter production of cotton roots, stems, and leaves, but decreased growth rate over time. The ODDA dry matter production of cotton roots, stems, and leaves was significantly higher than that of SPDA (Fig. 10). The dry matter from ODDA and SPDA cotton roots, stems, and leaves were the highest in 2019; and were 1%, 2%, and 3% higher in ODDA than SPDA, respectively. However, the increase in dry matter production was greater in SPDA than in ODDA. Compared with 2012, in 2019 the dry matter production of cotton roots, stems, and leaves, respectively, increased in ODDA by 39%, 126%, and 84% and SPDA by 41%, 129%, and 89%.

Cotton yield and yield factors

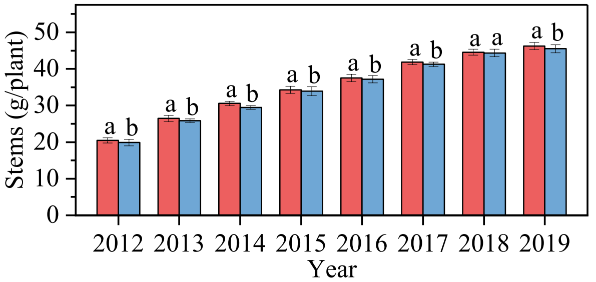
Over eight years, the 100-boll weight, effective boll (open bolls per plant) number, and cotton yield of ODDA and SPDA increased with the length of drainage treatments, but the rate of increase decreased year by year (Fig. 11). These factors were consistent cotton biomass. The results showed that the 100-boll weight, effective boll (open bolls per plant) number, and cotton yield of ODDA were significantly higher than those of SPDA. Both reached a maximum in 2019, and the 100-boll weight, effective boll number and yield of ODDA cotton were significantly increased by 2%, 3% and 7%, respectively, compared with SPDA. The minimum value was reached in 2012, and the 100-boll weight, effective boll number and yield of ODDA cotton were significantly increased by 2%, 2% and 16%, respectively, compared to SPDA. And the cotton yield increased 18.30 times and 19.96 times, respectively, in 2019 compared to that in 2012.

Economic benefits

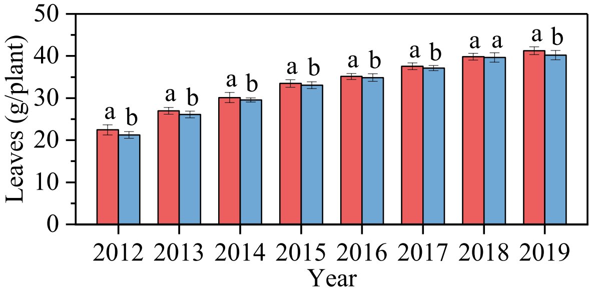
Figure 12 shows the economic benefits analysis based on the input and output for cotton cultivation for eight years. Annual depreciation charges for ODDA treatment and SPDA treatment are \$83 USD ha^{-1} and \$169 USD ha^{-1}, respectively. From 2012 to 2019, the total input cost for cotton production for the SPDA treatment was 19% lower than that of the ODDA treatment. Despite the high initial investment for the SPDA treatment, there was almost no annual operating cost over our eight-year investigation. Additionally, the SPDA treatment did not occupy land and it increased the income of cotton production compared to ODDA treatment. The annual operating cost for ODDA treatment for cotton cultivation in 2019 was 7.73 times higher than such costs in 2012. The net present value (NPV) of both SPDA treatment and ODDA treatment was greater than zero, which was economically feasible. The NPV and the annual rate of return on investment for the SPDA treatments were higher than for the ODDA treatment. Besides, the SPDA treatment had a shorter dynamic payback period than ODDA treatment, which were 6.34 years and 7.59 years, respectively.



(a) Cotton roots

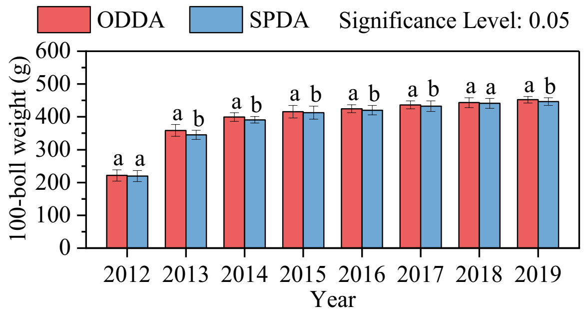


(b) Cotton stems

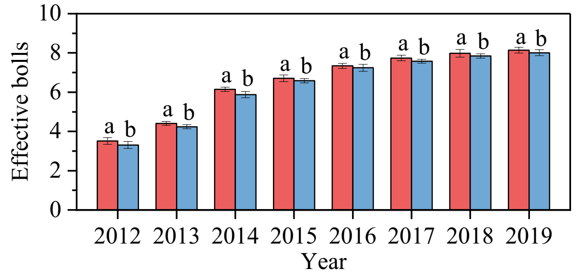


(c) Cotton leaves

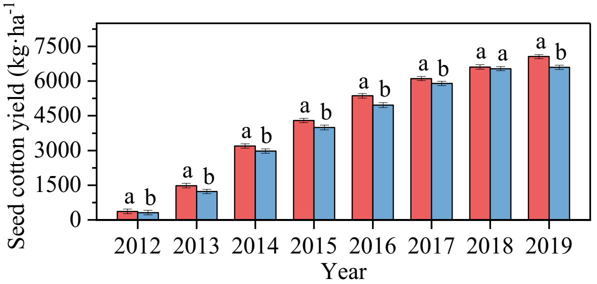
Fig. 10 Average (± SD) dry matter production of cotton roots (**a**), stems (**b**), and leaves (**c**) between 2012 and 2019. [1]Lowercase letters indicate significant differences ($P < 0.05$, *t* test uses the standard error of the mean) between treatments in each year. [2]ODDA, open ditch drainage treatment; SPDA, subsurface pipe drainage treatment



(a) 100-boll weight



(b) Effective boll number



(c) Yield

Fig. 11 Average (± SD) cotton 100-boll weight (**a**), effective boll (open bolls per plant) number (**b**), and yield (**c**) from 2012 to 2019. [1]Lowercase letters indicate significant differences ($P < 0.05$, *t* test uses the standard error of the mean) between treatments in each year. [2]*ODDA* open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment

Discussion

The effect of open ditch and subsurface pipe drainage technology on soil salinization

Open ditch and subsurface pipe drainage systems can effectively control soil salinization (Jia et al. 2011; Mastrocicco et al. 2013). Effective drainage measures can achieve rapid desalination of the upper soil layer in the short term and salt accumulation in the lower layer (Li et al. 2021; Liu et al. 2021), which was similar to the results of this study. Different from the short-term effect, the midterm effect was the overall desalination of the soil. After an 8 year field experiment, the changes of soil salinity in the 0–200 cm soil layer of ODDA and SPDA showed a stable trend, decreasing by 80.62% and 73.17%, respectively. The salinized soil was characterized by continuous desalination of the upper (0–80 cm) and lower (100–200 cm) layers, with the upper layer showing the most obvious desalination. Salt migrated from the upper soil layer to the lower layer, which gradually desalinated afterward (Shi et al. 2021). Here, the salt peak gradually migrated downwards over time, from a soil depth of 80–100 cm to 140–160 cm. The mulch (plastic film) suppresses the upward movement of soil water, which results in plant transpiration being the principal factor influencing water movement in the soil. Downward movement of water and salt was assured by the drainage systems—providing the means for the excess water to flow out of the rootzone. (Aernaguli et al. 2018). Due to the open ditch and the subsurface pipe drainage systems, the water in the farmland had a downward movement channel that drove the downward

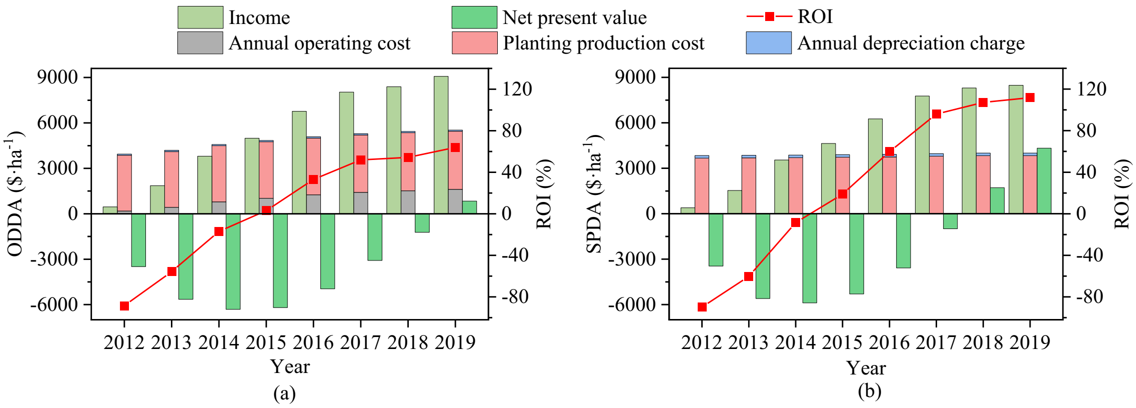


Fig. 12 Effects of drainage on income, net present value, annual operating and production costs from 2012 to 2019. [1]*ODDA* open ditch drainage treatment; *SPDA* subsurface pipe drainage treatment

movement of water and soil salt. The salinity moved downward with the irrigation water due to the leaching effect of the irrigation (Liu et al. 2021). Part of the soil salt leached into shallow groundwater, with most of the soil salt leaching into deeper soil layers and entering the open ditch or subsurface pipe with the water movement before being discharged. During the intermittent irrigation period, part of the salt in the shallow groundwater was transported to the soil and soil surface by phreatic evaporation. After the next irrigation and leaching cycle, salt returned to the shallow groundwater or deep soil layer and entered the open ditch or subsurface pipe before being discharged. During the growth period, there were small fluctuations in the salt content from the effects of evaporation, fertilization, and root water absorption. This process was repeated each year and the soil salinity decreased due the combined effects of snow and ice melt in the spring, irrigation and evaporation in the summer, and drainage system. With the long-term use of the drainage system, we speculate that the effect of drainage measures will gradually decrease when the salinity decreases to a certain level.

The salt content in drainage water is the most direct index of soil desalination rates in farmland (Chapman et al. 2005). We found that the drainage salinity of ODDA and SPDA showed a gradual decrease over time. Although the drainage salinity and pH fluctuated during the growing period. The groundwater salinity rose during the crop season while the drainage water salinity decreased and the salinity of the drainage water was generally higher than that of the groundwater throughout the experiment. This likely occurred because the groundwater sample was markedly influenced by the concentrating effects of crop water uptake, whereas the changes in the salinity of the drainage water reflected water flow paths from deeper depths, where the salinity of the soil water was much higher, causing the salinity of the drainage water to be greater than that of the groundwater (Quinn 2014; Alaya et al. 2014). The measured salinities of both the groundwater and drainage water were directly affected by bypass flow of the non-saline irrigation water to depths within and below the rootzone (Liu et al. 2014).

Open ditch and subsurface pipe drainage technology can control groundwater at the depth necessary for crop growth (Abdel-Dayem and Ritzema 1990; Liu et al. 2017). We found that the groundwater table level for SPDA was usually higher than for ODDA throughout the experiment, and the ability of open ditch drainage to control groundwater level was better than that of subsurface pipe drainage. This is because both open ditch and subsurface pipe drainage are used seasonally and intermittently in arid areas. Drip irrigation under mulch uses periodic irrigation and from the perspective of the soil profile, the beginning of each streamline in the soil flow field for open ditch and subsurface pipe drainage was perpendicular to the ground, with the end directed toward the ditch or subsurface pipe (Van der Molen et al. 2007). The hydraulic gradient caused by irrigation and crop water uptake resulted in water flow along the hydraulic gradient streamlines to the open ditch or the subsurface pipe, where the streamlines converged along the subsurface pipe (Afruzi et al. 2014; Chahar and Vadodaria 2012). In our study fields, the confluence surface of the open ditch was at the side wall of the open ditch, while that of the subsurface pipe was at the wall of the subsurface pipe, which had low porosity. The confluence area of the open ditch was much larger than the subsurface pipe; therefore, its drainage flow was much larger than the subsurface pipe. Therefore, the volume of salt discharged from the open ditch was greater than the subsurface pipe, and the control of the groundwater was better than the subsurface pipe.

Effects of open ditch drainage and subsurface pipe drainage on cotton dry matter weight, yield, and yield factors

The accumulation of cotton biomass is the basis for obtaining high-yield and high-quality cotton (Ren et al. 2021). Cotton has some salt tolerance; its organs and tissues have different salt sensitivities (Zhang et al. 2018). With drip irrigation under mulch, 85% of the cotton roots were distributed in the 30–50 cm soil layer (Yang et al. 2017). Soil salinity can have a significant influence on cotton growth (Pettigrew 2004). A soil salinity greater than 7 mS cm^{-1} reduced cotton yield, quality, and the dry weight of the cotton (Dong 2012). In this study, the effects of open ditch and subsurface pipe drainage on cotton growth were represented by changes in the dry matter weight of roots, stems, and leaves. With drainage treatments over time, the soil salinity decreased, which promoted cotton growth and the accumulation of dry matter (Miura and Tada 2014). The dry matter weight in ODDA was significantly higher than that in SPDA. Open ditch and subsurface pipe drainage technology can significantly improve crop yield (Feng et al. 2017; Tolomio and Borin 2019). We found that annual drainage treatments reduced soil salt content and increased 100-boll weight, effective boll number, and cotton yield over time. The faster the desalination rate, the more significant the yield improvement effect observed.

Analysis of the economic benefits of open ditch and subsurface pipe drainage treatment

The ultimate goal of open ditch and subsurface pipe drainage systems is to increase crop yield and income by improving saline–sodic land. Economically, the SPDA treatment required a high initial one-time investment for construction, but the area where cotton could be grown increased, increasing the income. Therefore, the net present value was – 1 to 414% higher than that of the ODDA treatments from 2012 to 2019. In this study, the payback periods of ODDA and SPDA were 7.59 and 6.34 years, respectively. In this 8-year operation cycle, the average annual investment of ODDA was 19% higher than that of SPDA. This increase in the ODDA average annual investment was primarily due to income losses from dredging and land occupation (Chen 2016). There was a significant difference in net profit between ODDA and SPDA even though the average annual ROI of ODDA (12%) was lower than that of SPDA (30%), which was primarily because the subsurface pipe drainage did not occupy arable land, and there were no annual operation and dredging costs. Although the income of open ditch drainage was relatively high, it needed regular dredging, occupied arable land that could have been used for planting, and was not conducive to the operation of large agricultural machinery, which contributed to its low return on investment (Yu et al. 2012). Therefore, subsurface pipe drainage has a more significant return on investment than open ditch drainage. Subsurface pipe drainage could be the most popular method used in Xinjiang.

Conclusions

To solve the problem of irrigation without drainage and salt accumulation with drip irrigation under mulch, open ditch and subsurface pipe drainage technology can remove soil salt from farmland. Our eight-year field experiment of open ditch and subsurface pipe drainage systems used with drip irrigation under mulch reached the following conclusions:

(1) Both open ditch and subsurface pipe drainage effectively reduced total soil salinity and improved saline–sodic soil. The desalination effect of open ditch drainage was better than that of subsurface pipe drainage. Soil desalination was continuous in the upper soil layer, while the lower layer first accumulated salt and then desalinated. The salinity and pH of ODDA and SPDA drainage water samples decreased throughout the experiment, following a decrease in soil salinity. The effect of open ditch drainage on groundwater level was better than that of subsurface pipe drainage, indicated by a significantly lower groundwater salinity in ODDA than SPDA.

(2) Over time, the drainage treatments increased cotton biomass, 100-boll weight, effective boll number, and yield in ODDA and SPDA. The ODDA yield was higher than that in SPDA, but the effect on increased yield was lower in ODDA than in SPDA.

(3) The payback period and eight-year ROI were better in SPDA than ODDA. Subsurface pipe drainage technology had higher economic benefits than open ditch drainage technology. These drainage technologies can both improve saline–sodic land to increase crop yield and income. The economic benefits of subsurface pipe drainage were more prominent in the long term.

(4) The midterm use of the technical model of drip irrigation under mulch supported by open ditch or subsurface pipe drainage may cause other ecological problems, such as the formation of bottom soil layers that are difficult to plow, which would inhibit irrigation water from washing salt into these deep soil layers. This would further impede the salt washing effect of the drainage technology. More research is needed to understand the midterm ecological effects of drainage treatments. Additionally, further research is needed to determine the viability of customizing irrigation and desalination management systems for specific alkali soil conditions.

Author contributions ZB: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, visualization. HL: conceptualization, validation, original draft preparation, data curation, project administration, funding acquisition. JL: Methodology, Validation, Supervision, Formal analysis, Writing—review and editing. ML: methodology, validation, supervision. PG: software, resources. PL: formal analysis. LL: investigation.

Funding This work was supported by the National Natural Science Foundation of China (grant numbers 52069026, U1803244,); Xinjiang Production and Construction Corps (grant number 2020DB001, 2021BC003).

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent to participate All authors read and approved the final manuscript.

Consent for publication All the authors agreed to publish the final manuscript.

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