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Modeling salinity risk response to irrigation practices for cotton production under film mulched drip irrigation in Xinjiang

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ABSTRACT

Predicting the impacts of the irrigation amount (*IA*), water salinity (*WS*), and antecedent soil salinity (*AS*) on soil salinization, the crop yield, and water productivities (*WPs*) are important for precision agriculture. We used a calibrated HYDRUS – 2D model coupled with a validated crop water production function to quantitatively determine the response of a soil – cotton system to three factors (*IA*, *WS*, and *AS*) in 30 scenarios under film mulched drip irrigation. These scenarios included five *IAs*, two *ASs*, and three *WSs*. Under the same *IA* and *WS*, the transpiration, evapotranspiration, yield, and *WPs* were lower, whereas the evaporation, drainage, soil water storage, and leached salt were higher under higher *AS* (over the salt tolerance threshold of cotton) scenarios. Under lower *AS* scenarios, desalination processes (20.2 to 166.8 g m^{-2}) occurred in freshwater (0.38 dS m^{-1}) irrigation scenarios and salt accumulated (425.8 to 1,442.4 g m^{-2}) in saline water (3.10 and 7.42 dS m^{-1}) irrigation scenarios. Desalination processes (2,273.4 to 4,692 g m^{-2}) occurred in the higher *AS* scenarios. Salinity risk warning should be the focus for cotton fields with lower *AS* and saline water irrigation. Our results may help to identify the salinity risk to support sustainable cotton production in Xinjiang.

Key words: evapotranspiration components, HYDRUS – 2D, intelligent irrigation, saline water irrigation, soil water/salt balance, water productivity

HIGHLIGHTS

- Desalination occurred in cotton fields under higher soil salinity scenarios.
- Cotton fields with lower antecedent soil salinity and irrigated saline water poses a salinity risk.
- Water/salt balance components, yield, and water productivities functions of irrigation amount and water salinity.

1. INTRODUCTION

Salinization is recognized as a threat to global food security and agricultural productivity, mainly in arid and semiarid regions (Al-Tabbal & Al-Zboon 2021). This process is accelerated by human activities, such as inadequate irrigation management. All water used for irrigation contains soluble salts, and thus there is an inherent salinity risk under irrigation due to unavoidable changes in the soil water/salt balance (Ning *et al.* 2020, 2021).

The saline–alkali soil area of Xinjiang comprises about one–third of that in China (Chen *et al.* 2010) and 37.72% of the existing cultivated land has been affected by salinization. In Xinjiang, soil salinization reduces the grain output by 8.6% and the cotton output by 9%. The economic loss caused by soil salinization accounted for about 8% of the annual planting industry output. Xinjiang is the largest cotton growing region in China with about 78% of the planted area and 87% of the yield, and nearly half of the local farmers are engaged in cotton growing (Ning *et al.* 2013, 2015, 2021). The film mulched drip irrigation (FMDI) technique has been implemented widely for cotton production in Xinjiang, but the sources of irrigation water are often brackish due to the scarcity of fresh water for agriculture (Chen *et al.* 2010; Liu *et al.* 2012, 2013).

Sustainable cotton productivity in Xinjiang is challenged severely by the growing risk of salinization due to FMDI. Ning *et al.* (2014) reviewed the effects of the irrigation regime under FMDI on the soil water and salt movement characteristics in cotton fields. To achieve higher cotton yields, greater water productivities (*WPs*), and promote salt leaching, the recommended irrigation amount (*IA*) is about 370 mm with a high irrigation frequency of 5 days under FMDI in northern Xinjiang (Liu *et al.* 2013; Ning *et al.* 2021). Chen *et al.* (2010) reported that irrigation with brackish water significantly increased the accumulation of salt in the root zone. Liu *et al.* (2012, 2013) reported the effects of the irrigation regime and water quality on the soil salinity, soil moisture, and cotton yield based on field experiments, where the results showed that the cotton yield and *WPs* decreased as the irrigation frequency and water quality decreased. Compared with irrigation using freshwater, Wang *et al.* (2017) found that irrigation using brackish water at a reasonable timing and duration were beneficial for the cotton yield. Ning *et al.* (2021) evaluated the effects of the irrigation schedule (*IA* and irrigation frequency) and antecedent soil salinity distribution (*AS*) on the soil water/salt balance and *WPs* under FMDI. However, little information is available regarding the quantitative effects of the *AS* profile, *IA*, and irrigation water salinity (*WS*) on the response of the soil–cotton system under FMDI.

In order to facilitate intelligent irrigation, managers and researchers require adequate assessment of the effects of irrigation on cotton production and the soil environment under FMDI. Unfortunately, it is still very problematic to systematically determine the soil water and salt balance in the root zone, cotton yield, and *WPs* under typical irrigation schedules in cotton fields. Ning *et al.* (2021) investigated the probable reasons for these difficulties and proposed a validated hydrological model coupled with a crop water production function to successfully address this problem. The validated HYDRUS – 2D model with a modified root water uptake (RWU) function coupled with a validated crop water production function was used to estimate the effects of the *IA* and irrigation frequency and *AS* on the soil water/salt balance, plant water status, and leaching fraction (LF), as well as the cotton yield and *WPs* under FMDI in 36 scenarios based on a two-year field experiment conducted previously by Ning *et al.* (2015). Moreover, the irrigation schedules in typical cotton fields were also optimized to increase the yield and water productivities under FMDI (Ning *et al.* 2021).

Predicting the effects of irrigation on the soil salinity risk and agricultural ecosystem is crucial for sustainable agricultural development in arid and semi-arid areas. In the present study, we systematically investigated the effects of *IA*, *WS*, and *AS* on the response of the soil–cotton system and the salinity risk under FMDI. Understanding the impacts of FMDI should help to effectively predict and reduce the soil salinity risk to allow sustainable cotton production in Xinjiang. Thus, in this study, we established the quantitative relationships for the soil water/salt balance components, cotton yield, water productivities as functions of irrigation amount and water quality in typical saline–alkali cotton fields.

2. MATERIALS AND METHODS

2.1. Site description

Field experiments were conducted during 2011 and 2012 in moderate–severe saline soil at Manas Cotton Breeding Station (44°18′N, 86°22′E, 438 m above sea level), which is located in the Manas Oasis on the southern alluvial plain, Xinjiang, China (Figure 1).

The experimental site has a typical continental arid climate, with a mean annual temperature of 6.6 °C, average annual rainfall of 147 mm, and annual evaporation ranging from 1,500 to 2,100 mm. The groundwater table is around 4 m below the surface.

2.2. Field experiment

In 2011, cotton (*Gossypium hirsutum* L. cv. 07–5) was planted using the traditional 'one film, two tapes, and four rows' planting mode. Four treatments were tested comprising two *IA* values of 300 and 375 mm with two irrigation *WS* values of 0.38 dS m^{-1} from a deep aquifer (25 m from the soil surface) and 3.10 dS m^{-1} from a shallow aquifer (5 m). In 2012, cotton was planted using the 'one film, three tapes, and six rows' mode. The treatments tested comprised two *IA* values of 450 and 500 mm with two irrigation *WS* values of 0.38 and 3.10 dS m^{-1}. Every experiment was replicated three times with irrigation, 10 times in total. Cotton under FMDI was sown in April and harvested in September. Further details of the field experiment were described previously by Ning *et al.* (2015).

Soil samples were collected at depth intervals of 10 cm at five locations perpendicular to the drip tape or planting row. Samples were collected 10 times and once before each irrigation event. The sampled soil was measured to determine the soil water (gravimetrically) and salinity. Soil profiles (0–150 cm) were obtained for three soil layers (Table 1). Soil water retention curves were determined for the three soil layers by using the pressure membrane method with undisturbed soil samples collected from the field. The soil hydraulic parameters used in this study are presented in Table 1.

Figure 1 | Location of the experimental site.

Table 1 | Soil hydraulic parameters and solute parameters for the field experiments used in the simulations (Ning *et al.* 2015)

Depth (cm)	Texture class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	K_s (cm d^{-1})	α_L (cm)	α_T (cm)
0–20	Silt clay loam	0.063	0.388	0.086	1.69	40	30	3
20–80	Silt loam	0.058	0.358	0.092	1.46	28	20	2
80–150	Loam	0.073	0.418	0.093	1.48	65	10	1

Note: θ_r and θ_s are the residual and saturated water contents; α and n are the fitting parameters of the van Genuchten (1980) equation; K_s is the saturated hydraulic conductivity; α_L is the longitudinal dispersivity; α_T is the transverse dispersivity.

Root samples were collected four times (squaring, early bloom, full-bloom, and boll stages) in each growing season using an auger with an inner diameter of 8 cm and height of 10 cm. Root length and rooting depth measurements were interpolated using the Kriging method to generate root distributions in different growth stages (Ning *et al.* 2015). Shoot and leaf samples were collected every 10–20 days.

2.3. Numerical modeling, and initial and boundary conditions

The HYDRUS–2D model described by Šimůnek *et al.* (2011) was employed to simulate the two-dimensional soil water flow and solute transport under FMDI. Based on the field experiment conducted in 2011, the HYDRUS–2D model was employed to simulate a rectangular flow domain, comprising the soil profile from the middle of the film to the center of the bare soil surface, and the vertical distances was 150 cm (Figure 2).

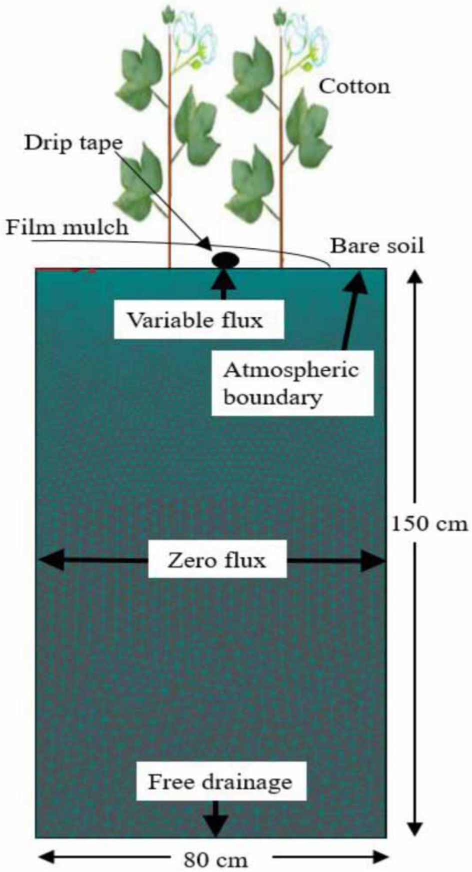

Figure 2 | Schematic view of the HYDRUS–2D spatial modelling domain.

A time-variable flux boundary representing drip irrigation was imposed in the surface saturated zone of the film-mulched soil surface. The remaining mulch-covered upper regions were considered as a zero flux boundary. A time-dependent atmospheric boundary condition was used to represent the soil surface without mulch cover. Zero flux boundary conditions were set through the vertical edges of the flow domain. A free drainage boundary was specified at the base of the flow region. Third-type Cauchy (with the daily evaporation rate) boundary conditions were imposed in the flow domain. All of the specified boundary conditions are illustrated in Figure 2.

The measured soil water and salinity distributions were used as the initial conditions. The measured irrigation *WS* was used as a time variable input for soil salinity prediction. The normalized root density distribution function of cotton under FMDI determined by Ning *et al.* (2015, 2019) was used to describe the root distribution in HYDRUS–2D.

2.4. Model validation

It is commonly accepted that numerical models should be first calibrated and validated for the specific field conditions to obtain higher confidence in the outcomes predicted. We used previously calibrated and validated input parameters described in previous studies by Ning *et al.* (2015, 2021), because the same field was considered in the present study. Thus, we previously calibrated and validated the HYDRUS–2D model for the specific meteorological, location, soil, and crop conditions in the study region. The soil hydraulic parameters and solute parameters used as inputs (Table 1) were taken from the study by Ning *et al.* (2015), who employed the HYDRUS–2D model to simulate the two-dimensional soil water flow and solute transport in cotton fields under FMDI with a modified RWU function. Similarly, the critical values of the water and salinity stresses for water uptake by cotton were taken from our previous investigation of cotton production under FMDI in the study area (Ning *et al.* 2015). The simulated soil moisture results agreed well with the field measurements, where the root mean square error (RMSE) was less than 0.03 $cm^3\ cm^{-3}$, and the coefficient of determination (R^2) was greater than 0.65. The simulated and measured soil salinity distributions were also in good agreement, with a maximum RMSE of

8.84 dS m^{-1} and minimum R^2 of 0.65. Further details were provided by Ning *et al.* (2015). Furthermore, the calibrated HYDRUS–2D model coupled with a validated crop water production function was derived from Ning *et al.* (2021), who used the coupled model to simulate the effects of the irrigation schedule (*IA* and irrigation frequency) and *AS* on the soil water/salt balance, plant water status, LF, cotton yield, and *WPs* under FMDI.

Thus, in the current study, we evaluated the impacts of irrigation practices (such as *IA*, *WS*, and *AS*) in the same region considered in our previous studies.

2.5. Simulation scenarios

To quantify the impacts of three interacting factors (*AS*, *IA*, and *WS*) on the soil water/salt balance, cotton yield, and *WPs* under FMDI, 30 scenarios were established in this study.

The 30 scenarios were defined as combinations of two different *AS* distributions with five *IA* values and three *WS* values. The two typical measured *AS* profiles were derived from Chen *et al.* (2010) and Ning *et al.* (2021), and they are shown in Figure 3. Moreover, the recommended regional *IA* is equal to 70% evapotranspiration by cotton (70%ETc) in the Shihezi area (Liu *et al.* 2013; Ning *et al.* 2021), so five *IA* values were set as 60%ETc, 70%ETc, 80%ETc, 90%ETc and 100%ETc (Ning *et al.* 2021). The measured irrigation *WS* in the Shihezi area usually ranged from 0.38 to 7.42 dS m^{-1} (Chen *et al.* 2010; Liu *et al.* 2012; Ning *et al.* 2015), and thus three irrigation *WS* values were set as 0.38, 3.10, and 7.42 dS m^{-1}. The measured soil water distribution on 11 June, 2011 was used as the initial condition. The measured irrigation *WS* was used as a time variable input for soil salinity prediction. All simulations were performed from 11 June to 2 September, 2011. The combinations considered in the different scenarios are shown in Table 2.

2.6. Modeling soil water/salt balance, cotton yield, and *WPs*

2.6.1. Water balance components

During the irrigation season, the actual evapotranspiration (ET_a, mm) was calculated as follows (Ning *et al.* 2021):

$$ET_a = E_a + T_a = I + P - \Delta S - D \tag{1}$$

where I is the irrigation amount (mm), P is the precipitation (mm), ΔS is the change in the soil water storage in the root zone from 0 to 100 cm (mm), and D is the drainage (mm). Moreover, ET_a comprises the actual soil evaporation (E_a) and actual transpiration (T_a).

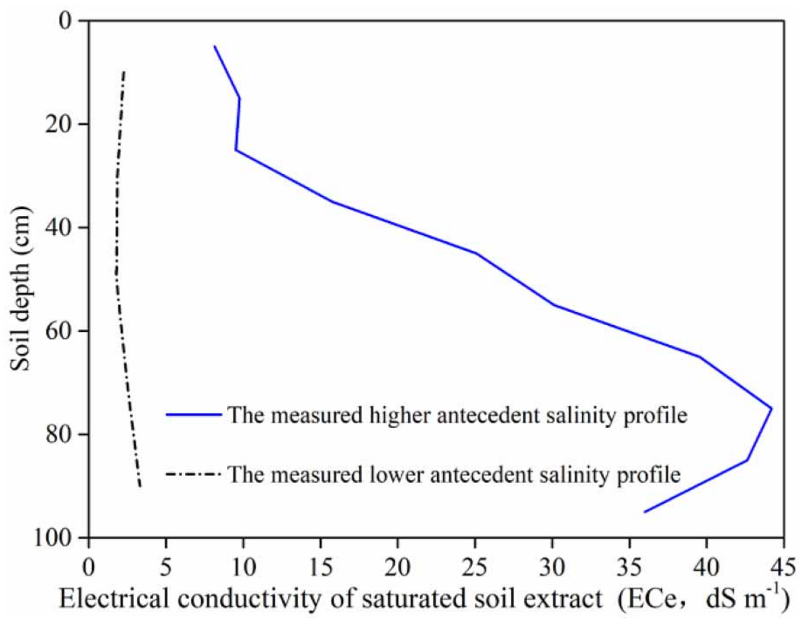

Figure 3 | Two measured lower and higher antecedent soil salinity profiles (Ning *et al.* 2021).

Table 2 | Combined scenarios modeled by the HYDRUS–2D model

	Lower antecedent soil salinity profile			Higher antecedent soil salinity profile	
Scenario	**Irrigation amount (*IA*)**	**Irrigation water salinity (*WS*, dS m^{-1})**	**Scenario**	**Irrigation amount (*IA*)**	**Irrigation water salinity (*WS*, dS m^{-1})**
1	60%ETc	0.38	16	60%ETc	0.38
2	60%ETc	3.10	17	60%ETc	3.10
3	60%ETc	7.42	18	60%ETc	7.42
4	70%ETc	0.38	19	70%ETc	0.38
5	70%ETc	3.10	20	70%ETc	3.10
6	70%ETc	7.42	21	70%ETc	7.42
7	80%ETc	0.38	22	80%ETc	0.38
8	80%ETc	3.10	23	80%ETc	3.10
9	80%ETc	7.42	24	80%ETc	7.42
10	90%ETc	0.38	25	90%ETc	0.38
11	90%ETc	3.10	26	90%ETc	3.10
12	90%ETc	7.42	27	90%ETc	7.42
13	100%ETc	0.38	28	100%ETc	0.38
14	100%ETc	3.10	29	100%ETc	3.10
15	100%ETc	7.42	30	100%ETc	7.42

2.6.2. Salt balance components

The simplified salt balance can be represented as follows (Ning *et al.* 2021):

$$\Delta SS = S_w - S_d \tag{2}$$

where ΔSS is the change in the salt storage in the root zone (g m^{-2}), and S_w and S_d are the quantities of salt added in irrigation water and leached by the percolation water (g m^{-2}), respectively. The salt storage in the root zone is in equilibrium when ΔSS equals 0, soil salt is accumulated when $\Delta SS > 0$, and more salt leaves the root zone when $\Delta SS < 0$.

2.6.3. Cotton yield and *WPs*

In our previous study (Ning *et al.* 2021), the cotton yield (Y, kg hm^{-2}) was calculated using ET_a based on a verified water production function under FMDI in the same field, as follows:

$$Y = -1.48 \times 10^{-2} \times ET_a^2 + 21.566 \times ET_a - 2{,}639.5 \tag{3}$$

The *WPs* for cotton (WP_{ETa}) and for irrigation (WP_I) were the cotton yield (Y) produced per ET_a and per unit amount of irrigation water (I), separately (Ning *et al.* 2021):

$$\mathrm{WP}_{ETa} = \frac{Y}{ET_a} \tag{4}$$

$$\mathrm{WP}_I = \frac{Y}{I} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. Water balance components

The effects of changes in the *AS*, *IA*, and *WS* values on the water balance components; that is, evaporation (E_a), transpiration (T_a), drainage (*D*), and soil water storage change (ΔS) in the root zone, were obtained from the HYDRUS–2D model, as shown in Table 3. Regression equations for the water balance components as functions of *IA* and *WS* are presented in Table 4.

3.1.1. Evaporation (E_a)

Compared with the mean E_a (96.2 mm) under the higher *AS* scenarios, the mean E_a value (88.8 mm) decreased by 7.63% in scenarios 1–15. The different values of *IA* and *WS* had little effect on the values of E_a. As *IA* increased from 60 to 100%ETc, the mean E_a increased in a narrow range from 95.5 to 96.8 mm in scenarios 16–30. The mean E_a raised in a narrow range from 95.9 to 96.5 mm in scenarios 16–30 as *WS* increased from 0.38 to 7.42 dS m^{-1}. Similarly, the increase in the mean E_a was small under the lower *AS* scenarios (scenarios 1–15) as *IA* or *WS* increased.

Under the different *AS* scenarios, the mean ratios of E_a relative to ET_a all decreased as *IA* or *WS* increased, where 21.58 to 22.86% and 31.83 to 38.27% of ET_a occurred at the soil surface under the lower and higher *AS* scenarios, respectively. The results indicated that a field under higher soil salt stress exhibited greater evaporation from the soil surface. *IAs* and *WSs* had relatively insignificant effects on E_a and the ratios of E_a to ET_a, thereby suggesting that E_a and the ratios of E_a to ET_a may be mainly affected by the film mulch. Ning *et al.* (2021) also found that the irrigation amount and frequency had little effect on E_a and the ratios of E_a to ET_a by using numerical modeling methods.

3.1.2. Transpiration (T_a)

The T_a (root water uptake) values decreased as *IA* reduced or *WS* increased (Figure 4). In scenarios 1–15, T_a increased from 281.7 to 329.2 mm. Compared with the transpiration with 60%ETc, the mean values of T_a with *IA* ranging from 70 to 100% ETc increased by 4.41%, 6.21%, 7.15%, and 7.09%, respectively.

The T_a values in scenarios 16–30 were lower than those in scenarios 1–15 under the same *IA* and *AS* (Figure 4). The lower T_a values in scenarios 16–30 ranged from 134.9 to 231.9 mm due to the higher salt stress. The mean values of T_a decreased by 8.62% and 22.09% as *WS* increased from 3.10 to 7.42 dS m^{-1}, compared with *WS* = 0.38 dS m^{-1}. This result suggests that the excess salt in the root zone may have reduced the soil water availability to crops and reduced transpiration by applying

Table 3 | Simulated components of water balance (mm) and salt balance (g m^{-2})

	Lower antecedent soil salinity profile							Higher antecedent soil salinity profile					
Scenario	E_a*	T_a*	D*	ΔS*	S_d#	ΔSS#	Scenario	E_a	T_a	D	ΔS	S_d	ΔSS
1	91.2	307.8	36.6	−34.4	90.7	−26.7	16	95.3	172.8	99.6	33.4	2,809.2	−2,745.2
2	87.4	305.1	32.2	−23.6	79.8	425.8	17	95.4	157.1	111.4	37.1	3,031.4	−2,525.8
3	87.5	281.7	32.6	−0.7	81.0	1,161.8	18	95.7	135.0	130.8	39.6	3,516.2	−2,273.4
4	91.2	320.6	36.9	2.4	94.2	−20.2	19	95.6	191.3	123.8	40.4	3,329.8	−3,255.8
5	87.4	320.8	44.9	−1.9	107.7	476.9	20	95.9	173.5	140.1	41.7	3,610.9	−3,026.3
6	87.5	292.7	47.8	23.1	118.9	1,313.9	21	96.1	147.4	163.4	44.2	4,153.8	−2,721.0
7	91.3	327.4	64.4	18.0	150.4	−66.4	22	96.0	207.8	153.5	43.8	3,878.6	−3,794.6
8	87.5	324.4	65.0	24.3	154.7	508.9	23	96.3	189.5	170.8	44.5	4,137.9	−3,474.3
9	87.7	298.3	76.4	38.7	210.1	1,412.7	24	96.6	161.7	197.0	45.8	4,720.1	−3,097.4
10	91.3	329.2	96.8	33.8	207.7	−113.7	25	96.2	220.9	186.5	47.6	4,365.8	−4,271.8
11	87.7	328.3	97.5	37.6	234.6	508.0	26	96.6	202.7	205.0	46.9	4,620.8	−3,878.2
12	87.9	301.0	115.8	46.4	370.3	1,442.4	27	96.9	173.3	233.3	47.6	5,237.1	−3,424.3
13	91.3	328.1	132.6	49.2	270.8	−166.8	28	96.4	232.0	222.9	49.8	4,796.0	−4,692.0
14	87.8	327.7	140.7	44.9	344.1	477.5	29	96.8	213.6	241.3	49.5	5,044.0	−4,222.4
15	88.2	302.2	160.7	50.1	574.6	1,292.4	30	97.2	181.0	271.2	51.8	5,705.5	−3,838.6

Note: * and # represent the water balance components and salt balance components, respectively.

Table 4 | Regression equations for water balance components as functions of *IA* and *WS*

Scenario	Regression equation	RSME	R^2
1–15	$E_a = 93.16 - 0.01 \times IA - 2.23 \times WS + 0.20 \times WS^2$	0.05	0.99
	$T_a = 136.11 + 0.80 \times IA + 2.32 \times WS - 0.79 \times WS^2$	1.10	0.99
	$ET_a = 229.28 - 0.80 \times IA - 0.08 \times WS - 0.59 \times WS^2$	1.09	0.99
	$D = 226.84 - 1.27 \times IA - 8.60 \times WS + 0.02 \times IA \times WS + 0.22 \times WS^2$	2.30	0.99
	$\Delta S = -375.0 + 1.47 \times IA - 8.52 \times WS - 0.021 \times IA \times WS - 0.001 \times IA^2 + 3.74 \times WS^2$	2.25	0.99
16–30	$E_a = 91.13 + 0.02 \times IA + 0.04 \times WS - 0.0002 \times IA \times WS - 0.005 \times WS^2$	0.03	0.99
	$T_a = 7.66 + 0.66 \times IA - 2.86 \times WS - 0.009 \times IA \times WS + 0.015 \times WS^2$	0.72	0.99
	$ET_a = 98.78 + 0.67 \times IA - 2.83 \times WS - 0.009 \times IA \times WS + 0.01 \times WS^2$	0.74	0.99
	$D = -51.64 + 0.135 \times IA + 11.887 \times WS + 0.012 \times IA \times WS - 0.231 \times WS^2$	0.75	0.99
	$\Delta S = -12.53 + 0.19 \times IA + 1.64 \times WS - 0.003 \times IA \times WS + 0.013 \times WS^2$	0.76	0.97

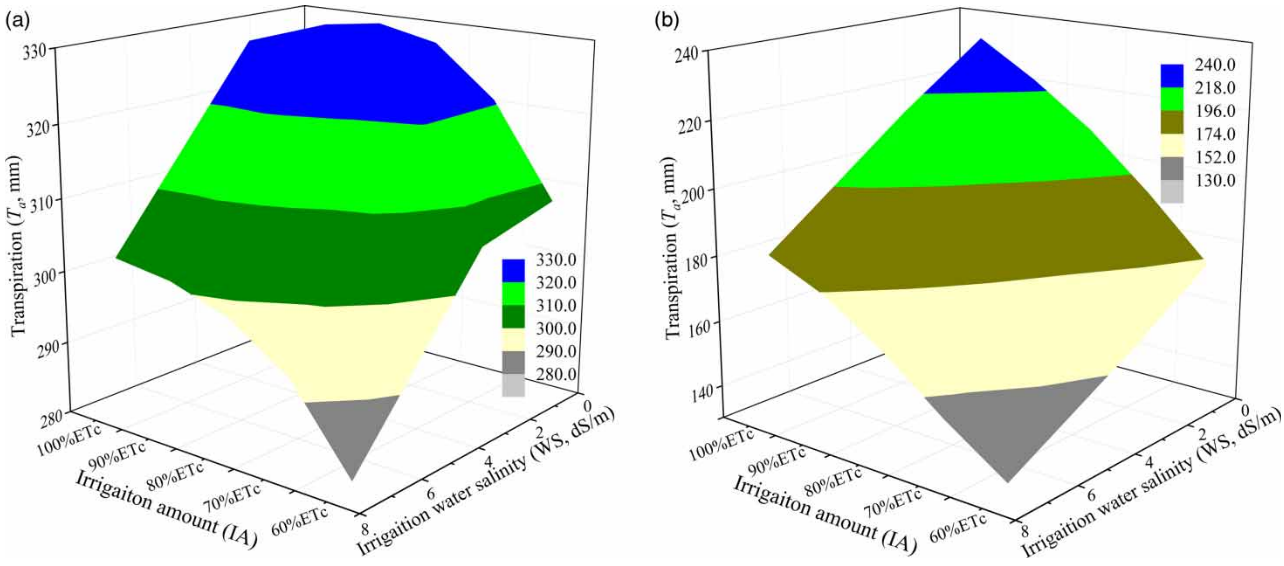

Figure 4 | Response surfaces of transpiration (T_a) under the lower antecedent soil salinity profile (a) and the higher antecedent soil salinity profile (b) for different simulation scenarios.

osmotic stress. This result also reflects the self-adaptability of the crops to salt stress conditions. Selim *et al.* (2012) reported a similar trend where the RWU decreased as *WS* increased due to the effects of salt stress. The transpiration decreased as *IA* of drip irrigation reduced (Ning *et al.* 2021).

3.1.3. Evapotranspiration (ET_a)

In the lower and higher *AS* scenarios, the mean values of ET_a varied from 386.9 to 408.4 mm and 250.4 to 305.6 mm as *IA* ranged from 60 to 100%ETc, respectively (Figure 5), thereby indicating a significant decrease in evapotranspiration under salt-stressed conditions. Ning *et al.* (2021) also reported that the cotton evapotranspiration was less under salt stress than that without salt stress. The average ET_a reduced from 413.8 to 408.4 mm and 300.8 to 256.2 mm as *WS* increased from 0.38 to 7.42 dS m^{-1}, respectively. Compared with the higher *AS* scenarios, ET_a increased significantly as *IA* increased under the lower *AS* scenarios.

Similarly, the measured cotton evapotranspiration under FMDI was 277 to 438 mm in an adjacent area according to Cai *et al.* (2002) and Wu *et al.* (2014). The relationship between *IA* and ET_a was proposed by Ning *et al.* (2021). The regression equations for ET_a as functions of *IA* and *WS* are shown in Table 4.

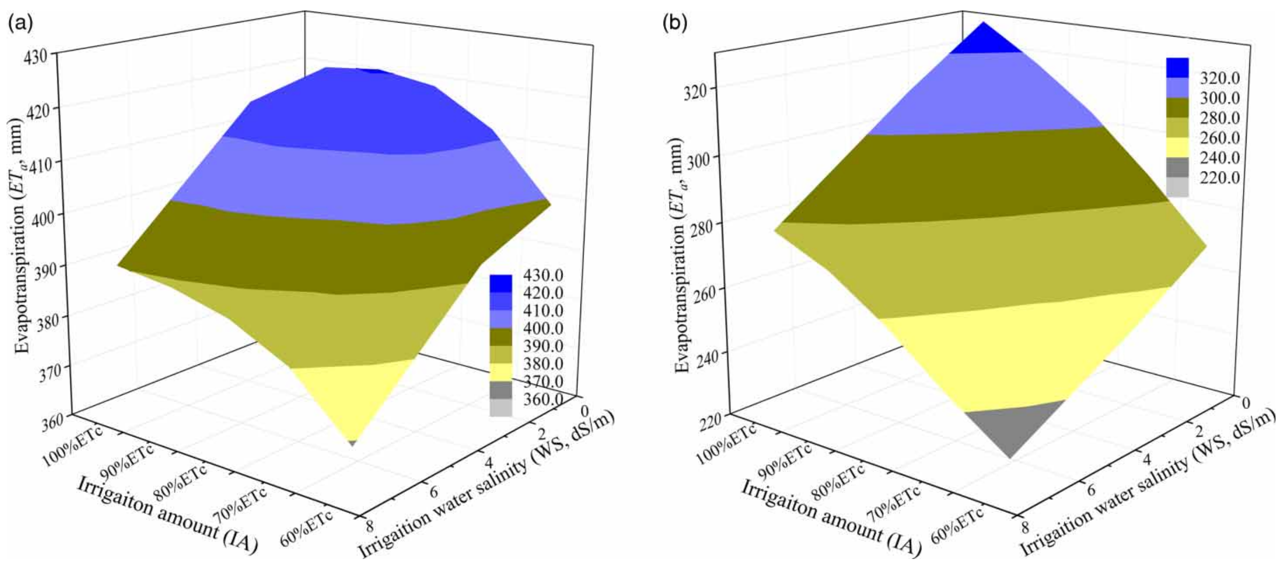

Figure 5 | Response surfaces of evapotranspiration (ET_a) under the lower antecedent soil salinity profile (a) and the higher antecedent soil salinity profile (b) for different simulation scenarios.

3.1.4. Drainage (*D*)

The applied irrigation water was less than or equal to the cotton ET_a, but D occurred below the root zone under FMDI. As expected, the highest D values occurred under the largest IA and WS levels. A lower mean D of 78.7 mm occurred in scenarios 1–15 than the mean D of 176.7 mm in scenarios 16–30. Thus, higher soil salt stress limited the RWU, so some fractions of the irrigation water subsequently drained away. Ning *et al.* (2021) also reported similar conclusions that D was higher under salt stress than that without salt stress in a cotton field under FMDI. Moreover, a considerable amount of D occurred under drip irrigation according to a previously reported numerical model (Phogat *et al.* 2013; Ning *et al.* 2021). D raised as IA or WS increased. In scenarios 16–30, compared with the mean D with 60%ETc, the mean values of D with IA ranging from 70 to 100%ETc increased by 24.98%, 52.51%, 82.75%, and 115.12%, respectively. The mean D increased by 10% and 26.61% for $WS = 3.10$ and 7.42 dS m^{-1}, compared with $WS = 0.38$ dS m^{-1}. Similar results were obtained in scenarios 1–15.

LF is defined as the ratio of D relative to IA, and it is usually used to quantify the leaching rate (Ning *et al.* 2020, 2021). In the lower and higher AS scenarios, the LF values ranged from 9.97 to 30.90% (mean = 17.67%) and 31.13% to 52.15% (mean = 41.38%), respectively, thereby indicating that LF was higher under salt stress than that without salt stress in the cotton field under FMDI. LF raised as IA or WS increased. Specifically, the mean LF values in 1–15 scenarios were 10.56%, 11.67%, 16.33%, 21.99%, and 27.82% when each IA value ranged from 60 to 100%ETc, respectively. The relative increases compared with 60%ETc were 16.57%, 54.62%, 108.19%, and 163.34% when IA ranged from 70 to 100%ETc, respectively. The relative decreases in LF were 3.14% and 16.90% for $WS = 3.10$ and 7.42 dS m^{-1}, respectively, compared with $WS = 0.38$ dS m^{-1}. Similar results were obtained in scenarios 16–30. Hanson *et al.* (2008) reported that 7.7%–11.3% of the irrigation water leached from the root zone after the application of 60% of the potential ET (severe deficit irrigation).

3.1.5. Water storage change (ΔS)

The ΔS values depleted in scenarios 1–3 and 5 (2.4–50.3 mm), and increased (2.4–50 mm) in scenarios 4 and 6–15. In scenarios 16–30, the ΔS values were compensated (33.4–51.8 mm) by the irrigation water. When IA was fixed, larger WS values led to higher ΔS values. Similarly, when WS was fixed, a larger IA value led to an increase in ΔS.

3.2. Salt balance components

Table 3 shows the salt balance components for each scenario; that is, leached salt (S_d) and salt storage change (ΔSS). In general, the initial soil salt storage (S1) values in the root zone were 1,080.8 and 13,601.7 g m^{-2} under the lower and higher AS scenarios, respectively. As IA increased from 60 to 100%ETc, the salt (S_w) added with the irrigation water increased by 64, 74, 84, 94, 104, and 114 g m^{-2} ($WS = 0.38$ dS m^{-1}) respectively, as well as by 505.6, 584.6, 663.6, 742.6, and 821.6 g m^{-2} with

Table 5 | Regression equations for salt balance components as functions of *IA* and *WS*

Scenario	Regression equation	RMSE	R^2
1–15	$S_d = 1{,}010.15 - 4.97 \times IA - 91.45 \times WS + 0.22 \times IA \times WS + 0.007 \times IA^2 + 1.74 \times WS^2$	16.72	0.98
	$\Delta SS = -1{,}498.87 + 7.26 \times IA + 122.64 \times WS + 0.21 \times IA \times WS - 0.009 \times IA^2 - 1.36 \times WS^2$	34.47	0.99
16–30	$S_d = -1{,}939.65 + 17.74 \times IA + 16.35 \times WS + 0.135 \times IA \times WS - 0.009 \times IA^2 + 5.77 \times WS^2$	14.65	0.99
	$\Delta SS = 1{,}450.75 - 15.45 \times IA + 14.85 \times WS - 0.30 \times IA \times WS - 0.007 \times IA^2 - 5.39 \times WS^2$	25.43	0.99

$WS = 3.10$ dS m^{-1}, and by 1,242.8, 1,432.8, 1,622.8, 1,812.7, and 1,866.9 g m^{-2} with $WS = 7.42$ dS m^{-1}. Regression equations for the salt balance components as functions of IA and WS are presented in Table 5.

3.2.1. Leached salt (S_d)

The mean S_d value of 4,197.1 g m^{-2} in scenarios 16–30 was higher than that of 205.9 g m^{-2} in scenarios 1–15 due to the higher soil salt stress. Figure 6 shows that increases in IA and WS accelerated the leaching of salt in the root zone (Ning *et al.* 2021). In scenarios 16–30, the mean values of D when IA ranged from 70 to 100%ETc increased by 18.57%, 36.12%, 52.01%, and 66.14%, respectively, compared with the mean S_d under 60%ETc. The mean S_d values increased by 6.60% and 21.66% for $WS = 3.10$ and 7.42 dS m^{-1}, respectively, compared with the mean S_d with $WS = 0.38$ dS m^{-1}. Increasing IA or WS could promote the leaching of salts from the root zone. Similar results were obtained in scenarios 1–15. Two linear relationships between S_d and IA, and S_d and D are presented in Figure 7.

3.2.2. Salt storage change (ΔSS)

Under the lower AS scenarios, desalination and salt accumulation processes always occurred during the irrigation season. Specifically, salt accumulated (425.8 to 1,442.4 g m^{-2}) in the scenarios under irrigation with saline water at 3.10 and 7.42 dS m^{-1}. The amount of accumulated salt increased as IA and WS raised. Compared with the mean accumulated salt amounts with 60%ETc for $WS = 3.10$ and 7.42 dS m^{-1}, the mean accumulated salt amounts when IA ranged from 70 to 100%ETc for $WS = 3.10$ and 7.42 dS m^{-1} increased by 12.80%, 21.04%, 22.85%, and 11.48%, respectively. The mean accumulated salt amounts were 479.4 and 1,324.6 g m^{-2} for $WS = 3.10$ and 7.42 dS m^{-1}, respectively. Phogat *et al.* (2011) noted that the mass of salt in the root zone increased under drip irrigation with deficit irrigation. In addition, soil salinization was

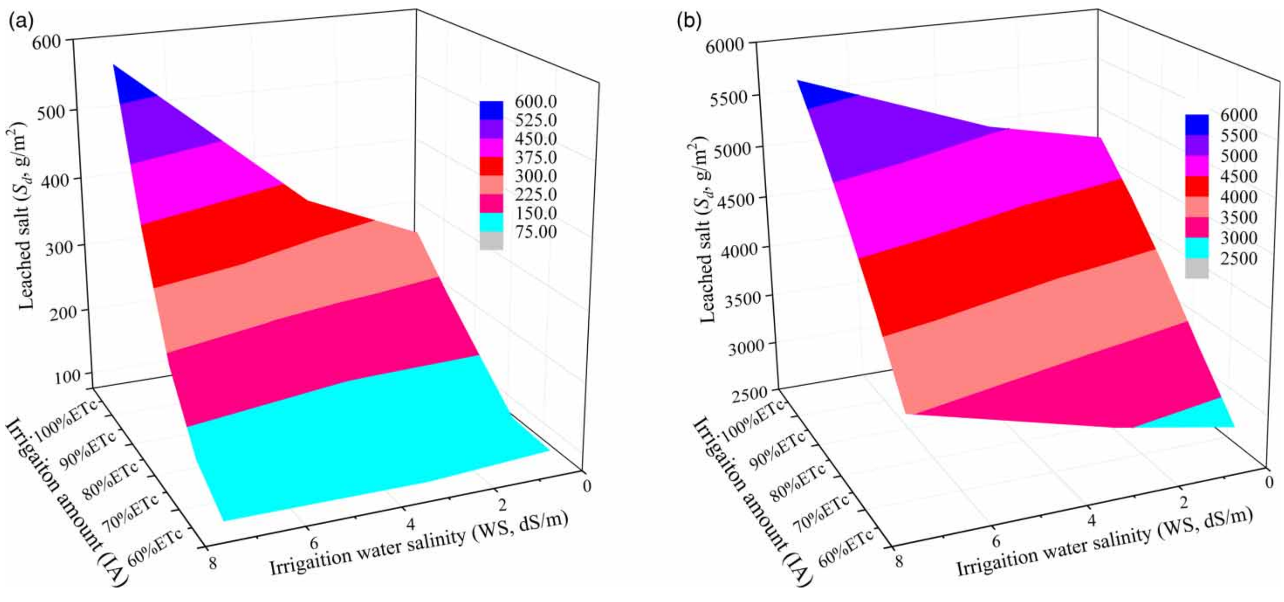

Figure 6 | Response surfaces of leached salt (S_d) under the lower antecedent soil salinity profile (a) and the higher antecedent soil salinity profile (b) for different simulation scenarios.

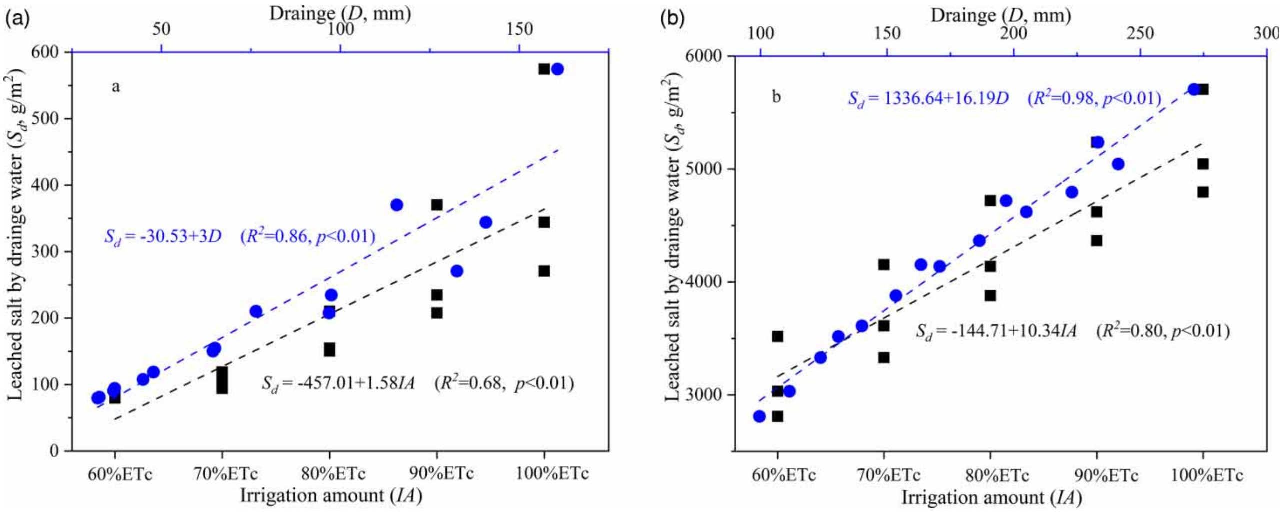

Figure 7 | Relationships between leached salt (S_d) and irrigation amount (*IA*), and leached salt (S_d) and drainage (*D*) under the lower antecedent soil salinity profile (a) and the higher antecedent soil salinity profile (b) for different simulation scenarios.

avoided by applying irrigation with freshwater ($WS = 0.38$ dS m^{-1}), and desalination (20.2 to 166.8 g m^{-2}) occurred in these scenarios. The desalination amount increased as *IA* increased. As *IA* increased from 60 to 100%ETc, the average amounts of salt leaving the root zone were 26.7, 20.2, 66.4, 113.7, and 166.8 g m^{-2}, respectively. Adequate leaching was important for the removal of salts from the root zone and for the long-term sustainability of the irrigated cotton field.

Moreover, desalination processes (2,273.4 to 4,692 g m^{-2}) occurred in scenarios 16–30 during the irrigation season. The desalination amounts increased as *IA* raised or *WS* decreased. As *IA* increased from 60 to 100%ETc, the amounts of stored salt in the root zone were 2,514.8, 3,001.0, 3,455.4, 3,858.1, and 4,250.9 g m^{-2}, respectively. The mean ΔSS values decreased by 8.70% and 18.15% for $WS = 3.10$ and 7.42 dS m^{-1}, respectively, compared with the mean ΔSS when $WS =$ 0.38 dS m^{-1}.

Based on an extensive field survey in a nearby region, Luo (2014) observed that the amount of salt accumulated in the cotton root zone was 321.2 g m^{-2} under a lower soil salinity distribution, whereas the desalination amount was 1,182.6 g m^{-2} in the root zone under a higher soil salinity distribution. Ning *et al.* (2021) also reported natural desalination amounts of 12.0 to 231.6 g m^{-2} and 2,739.7 to 5,291.9 g m^{-2} under lower and higher *AS* profiles, when using the current irrigation freshwater ($WS = 0.38$ dS m^{-1}) schedule under FMDI. Ning *et al.* (2021) also showed that increasing *IA* could promote soil desalination during the irrigation season. These results are consistent with those obtained in the present study.

3.3. Cotton yield (*Y*)

Salt stress affects the transpiration and evapotranspiration by crops, and it will inevitably affect the crop yield. Overall, *Y* was smaller under the higher *AS* scenarios (1,548 to 2,846 kg hm^{-2}) than the lower *AS* scenarios (3,305 to 3,812 kg hm^{-2}) due to the higher soil salt stress. *Y* increased as *IA* raised or *WS* decreased. In scenarios 16–30, the mean *Y* raised by 12.20%, 23.96%, 33.12%, and 40.07% as *IA* increased from 70 to 100%ETc, compared with the mean *Y* with 60%ETc. For a given *WS* value (i.e., 0.38 dS m^{-1}), the mean *Y* decreased by 8.95% and 23.68% for $WS = 3.10$ and 7.42 dS m^{-1}, respectively. Similar results were found in scenarios 1–15. Regression equation for *Y* as functions of *IA* and *WS* are shown in Figure 8.

In the same region where our study was conducted, Zhang *et al.* (2004) reported that the measured cotton yields under FMDI were 2,100 to 2,685 kg hm^{-2} in a severely high salinity field with 8 g salt per kg of soil. This result is close to the calculated *Y* value of 1,548 to 2,846 kg hm^{-2} under the higher *AS* scenarios. Moreover, the simulated cotton yields of 3,305 to 3,812 kg hm^{-2} were between the cotton yields under FMDI measured in the field by Wang *et al.* (2016) of 2,620 to 3,367 kg hm^{-2}, and by Zhang *et al.* (2004) of 4,815 to 4,920 kg hm^{-2} in a low salinity field (0.8 g salt per kg of soil). Under the lower *AS* scenarios, the simulated cotton yields were also similar to the cotton yields of 3,608 to 3,828 kg hm^{-2} estimated by Ning *et al.* (2021).

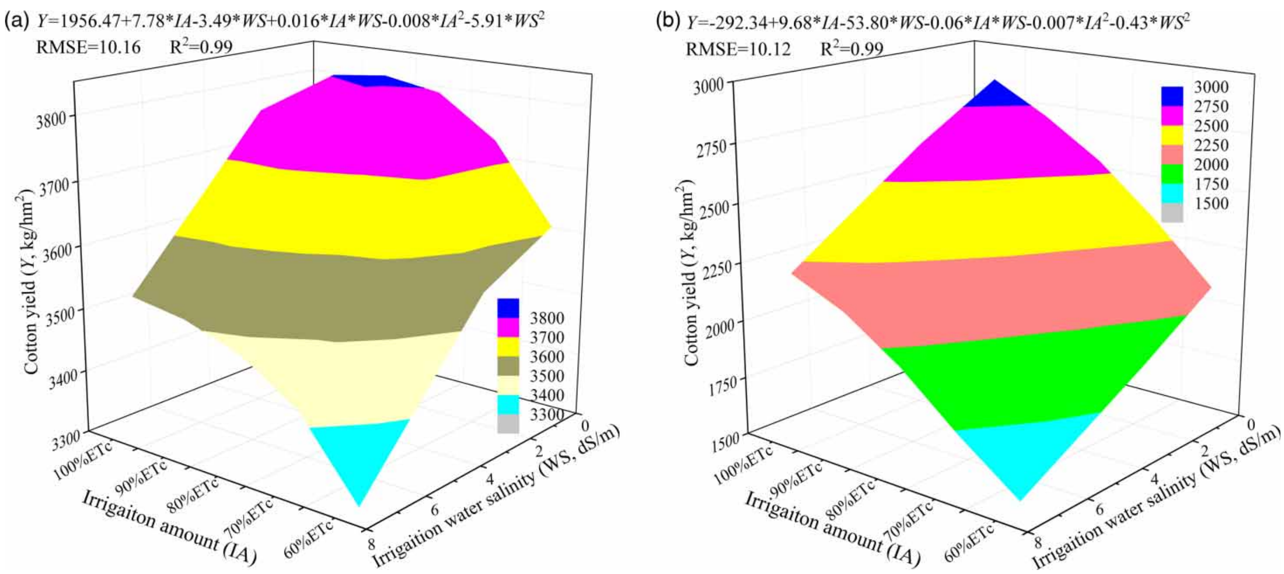

Figure 8 | Response surfaces of cotton yield (Y) under the lower antecedent soil salinity profile (a) and the higher antecedent soil salinity profile (b) for different simulation scenarios.

3.4. *WPs*

The *WPs* (WP_{ETa} and WP_I) indicates the necessity of improving irrigation management. A larger mean WP_{ETa} value of 0.90 (0.90 to 0.91) kg m^{-3} was obtained in scenarios 1 – 15 than scenarios 16 – 30 with an average WP_{ETa} of 0.79 (0.67 to 0.87) kg m^{-3}. Ning *et al.* (2013, 2021) reported similar WP_{ETa} values of 0.89 to 1.04 kg m^{-3} for cotton under FMDI in the same region.

WP_I ranged from 0.68 to 1.13 (mean of 0.89) kg m^{-3} and 0.43 to 0.65 (mean of 0.54) kg m^{-3} under the lower and higher *AS* scenarios, respectively. WP_I raised as *IA* or *WS* decreased. The mean WP_I values in scenarios 1–15 were 1.09, 0.98, 0.87, 0.79, and 0.71 kg m^{-3} for each *IA* ranging from 60 to 100%ETc, respectively. The relative decreases in WP_I were 1.3% and 8.12% for $WS = 3.10$ and 7.42 dS m^{-1}, respectively, compared with $WS = 0.38$ dS m^{-1}. Similar results were also obtained in scenarios 16 – 30. Wang *et al.* (2015) also reported similar results where the values of WP_I were 1.0 ± 0.3 kg m^{-3} based on 34 years of data obtained from a cotton field in the same area.

3.5. Identifying the salinity risk of cotton fields under FMDI

The salinity risk was analyzed based on the water and salt balances. There is a potential risk of soil salinization in cotton fields under FMDI. In general, desalination and salt accumulation processes coexisted in the cotton fields under FMDI during the irrigation season when *IA* and *AS* were different. Luo (2014) reported that salt accumulated in farmland under drip irrigation with a lower *AS* profile. Chen *et al.* (2010) indicated that the mean soil salinity profile in the root zone was 336 and 547% of the original soil profile based on a 3-year experiment under irrigation with saline water at 3.10 and 7.42 dS m^{-1}, respectively. In the present study, our results supported the previous conclusion that irrigating a cotton field with a lower *AS* profile (i.e., below crops salt tolerance threshold) using saline water (3.10 to 7.42 dS m^{-1}) will lead to salt accumulation in the root zone. The current irrigation schedule with saline water (3.10 and 7.42 dS m^{-1}) under FMDI for cotton in Xinjiang is not sustainable and it cannot satisfy the requirements for salt leaching. Thus, the key areas for warning and monitoring the potential salinity risk are these fields. We also suggest the alternate use of saline and freshwater for irrigation during the irrigation season or regular flood irrigation after the harvest to reduce the risk of soil salinity in the root area under FMDI.

By contrast, desalination occurred in the cotton field under the higher *AS* profile (i.e., above the crops salt tolerance threshold) using the current irrigation schedule (including saline water). Thus, the current irrigation practices in salt-affected fields could meet the requirements for salt leaching and crop growth during the irrigation season. As a consequence, flood irrigation after the harvest to leach salt may not be required under FMDI. Based on a four-year sentinel surveillance study under FMDI with the current irrigation schedule, in the same region where our study was conducted, Wang *et al.* (2014) and Li *et al.* (2016) reported that the soil salt in the root zone in cotton fields decreased in a salt–affected oasis area, which was beneficial for cotton production. The results obtained in the present study may help farmers and irrigation water management departments to identify and reduce the risk of soil salinity under FMDI in Xinjiang.

4. CONCLUSION

In this study, a calibrated HYDRUS–2D model coupled with a validated crop water production function was used to assess the interactive effects of *IA*, *WS*, and *AS* on the soil water and salt balance, cotton yield and *WPs* under FMDI. 30 scenarios were investigated with two *AS* values (lower and higher), five *IA* values (60%ETc, 70%ETc, 80%ETc, 90%ETc, and 100% ETc), and three *WS* values (0.38, 3.10, and 7.42 dS m^{-1}). The water balance components (i.e., T_a, ET_a, D, and ΔS) were significantly affected by *IA*, *WS*, and *AS*. The values of *IA* and *WS* had little effect on E_a. Lower T_a and ET_a values, and higher E_a, D, and ΔS values occurred in the higher *AS* scenarios due to the higher salt stress. The S_d values were greater in the higher *AS* scenarios than the lower *AS* scenarios under the same *IA* and *WS* values. Under the lower *AS* scenarios, desalination and salt accumulation processes occurred throughout the irrigation season. Desalination processes (2,273.4 to 4,692 g m^{-2}) occurred in the higher *AS* scenarios. The *Y* values were smaller under the higher *AS* scenarios (1,548 to 2,846 kg hm^{-2}) than the lower *AS* scenarios (3,305 to 3,812 kg hm^{-2}). Higher *WPs* values were gained under the lower *AS* scenarios. The *Y* and *WPs* values increased as *IA* increased or *WS* decreased.

It should be noted that cotton field with a lower *AS* profile (e.g., below the salt tolerance threshold of cotton) and irrigated with saline water (3.10, 7.42 dS m^{-1}) resulted in salt accumulating in the root zone (425.8 to 1,442.4 g m^{-2}). The key areas for warning and monitoring the risk of salinization are these fields under FMDI. Effective management strategies (such as alternate irrigation using saline and freshwater, etc.) to reduce the secondary salinity risk are also recommended in these cotton fields. The current irrigation practices in salt-affected fields could meet the requirements for salt leaching and crop growth. The results obtained in this study may facilitate the accurate identification and reduction of soil salt accumulation, and sustainable agricultural development in arid regions.

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DECLARATIONS OF INTEREST

None.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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