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Evaluation of mulched drip irrigation for cotton in arid Northwest China

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Abstract Field experiments were conducted in arid Southern Xinjiang, Northwest China, for 3 years to evaluate sustainable irrigation regimes for cotton. The experiments involved mulched drip irrigation during the growing season and flood irrigation afterward. The drip irrigation experiments included control experiments, experiments with deficit irrigation during one crop growth stage, and alternative irrigation schemes in which freshwater was used during one growth stage and relatively saline water in the others. The average cotton yield over 3 years varied between 3,575 and 5,095 kg/ha, and the irrigation water productivity between 0.91 and 1.16 kg/m^3. Crop sensitivities to water stress during the different growth stages ranged from early flowering-belling (most sensitive) > seedling > budding > late flowering-belling (least sensitive), while sensitivities to salt stress ranged from late flowering-belling > budding > seedling > early flowering-belling. Although mulched drip irrigation during the growing season caused an increase in salinity in the root zone, flood irrigation after harvesting leached the accumulated salts to below background levels. Numerical simulations, based on the 3-year experiments and extended by another 20 years, suggest that mulched drip irrigation using alternatively fresh and brackish water during the growing season and flood irrigation with freshwater after harvesting is a sustainable irrigation practice that should not lead to soil salinization.

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Introduction

Southern Xinjiang in Northwest China is an arid region with a very high evaporative demand and a general shortage of freshwater resources. While the mean annual precipitation is only 58 mm, the potential evapotranspiration rate equals 2,540 mm (Wang et al. 2010). Mulched drip irrigation, which saves water and increases water use efficiency as compared to furrow irrigation (Ibraginmov et al. 2007), is widely used in the area to irrigate cotton, a major cash crop in Xinjiang (Hou et al. 2009). Cotton yields generally decrease with a reduction in irrigation, irrespective of whether conventional irrigation technologies or drip irrigation is used (Singh et al. 2010; Ünlü et al. 2011), and are also limited by poor quality of irrigation water and related problems of soil salinization (Leidi and Saiz 1997; Vulkan-Levy et al. 1998; Qadir and Shams 1997; Henggeler 2004; Chen et al. 2010).

Field experiments are a critical component of any study delineating irrigation management strategies that are most effective in enhancing cotton productivity while

safeguarding local soil and water resources. At the same time, process-based numerical models are needed for optimal analysis of the data and extrapolation to decadal or longer time periods to more precisely understand the long-term effects of alternative practices. Computer simulation models for these reasons have become important tools for analyzing site-specific irrigation, soil salinization, or crop production problems (Skaggs et al. 2006). Many software packages simulating relevant water flow, solute transport, and root water uptake processes could potentially be used for this purpose, such as SWAP (van Dam et al. 1997; Kroes and van Dam 2003) and the HYDRUS codes (Šimůnek et al. 2008), which have been applied to a number of cotton irrigation studies (e.g., Singh 2004; Forkutsa et al. 2009). The HYDRUS (2D/3D) code (Šimůnek et al. 2006, 2012) in particular has been found useful in numerical analyses and optimizations of surface and subsurface drip irrigation schemes (e.g., Skaggs et al. 2004; Fernandez-Galvez and Simmonds 2006; Hanson et al. 2008; Roberts et al. 2009; Kandelous et al. 2011; Rodriguez-Sinobas et al. 2012).

To our knowledge, no numerical studies have been carried out thus far to formulate guidelines for a system that involves a combination of mulched drip irrigation with both saline and freshwater during the growing season and flood irrigation with freshwater after harvesting, while simultaneously adjusting irrigation quantities as a function of the growth stage of cotton. Such integrated numerical studies are relatively difficult because of the multidimensional nature of the flow regime and the complexity of imposing time-variable boundary conditions for combined mulched drip and flood irrigation systems. These are exactly the type of problems being addressed in this study using HYDRUS (2D/3D).

In order to evaluate sustainable irrigation regimes of mulched drip irrigation with saline water and calibrate HYDRUS for the long-term simulations, field experiments were conducted in Southern Xinjiang for typical local climate, and soil and cotton management conditions. Specific objectives of the research were to (1) compare cotton yields for different irrigation regimes, (2) characterize the spatial and temporal variability of the soil salinity of the root zone for different treatments, (3) calibrate and test the HYDRUS simulations using the experimental data, and (4) use the calibrated model to evaluate the long-term effects of alternative irrigation schemes.

Materials and methods

Experimental site

The experiments were carried out in cotton fields located in the Tarim Basin of Xinjiang, Northwest China, between March 2008 and September 2010. The area has an extreme arid climate with annual precipitation and potential evapotranspiration rates of approximately 58 and 2,540 mm, respectively. The study area is located 901 m above mean sea level and has a mean annual temperature of 11.5 °C, with very warm summers and relatively cool winters. There is an abundant supply of sunlight in the area, on average more than 8 h per day. The mean annual wind speed is approximately 0.77 m/s. Surface water used for irrigation comes from the Kongque River, whose water quality is affected by nearby Bosten Lake and has electrical conductivity (EC) values generally between 0.9 and 1.6 dS/m (He et al. 2010). Groundwater, having EC values between about 3–5 dS/m (see Table 1), is used often also for irrigation of cotton, which is known to have a relatively high tolerance for salinity (Maas 1990; Vulkan-Levy et al. 1998; Henggeler 2004; Steppuhn et al. 2005; Chen et al. 2010). The sodium adsorption ratio (SAR) of irrigation water ranged from 3.77 to 9.97. Loamy sand was the predominant soil texture at the field site. Electronic digital water level gauges were installed in the fields to monitor the water table. Drainage canals had their bottoms 2 m below the soil surface.

Irrigation treatments

The mulched irrigation experiments were conducted in three replicates on randomly selected field plots, each having a size of 10 m × 22.5 m. Quantities of applied irrigation water and their distribution during the growing season followed traditional irrigation patterns of cotton in the area (Table 2). Tables 3 and 4 summarize the deficit, control, and alternative irrigation experiments that were carried out, and how water was applied during the different growth stages of cotton. Five cotton growth stages are usually recognized: seeding (from germinating to budding, lasting about 20 days), budding (about 15 days), early flowering-belling (about 20 days since flowering), late flowering-belling (extends until boll opening, about 40 days), and boll opening (until harvest, about 30 days). Specifically, the following treatments were studied:

1. *Control irrigation* (Table 4): The total quantity of irrigation water throughout the entire growth season was 4,200 m³/ha, and either freshwater (denoted by the letter F) or more saline water (S) was used for irrigation.
2. *Deficit irrigation* (Table 3): 70 % of the irrigation demand was used during one crop growth stage (compared to control irrigation) and 100 % in the others. Deficit irrigation scenarios are denoted by the letter D.

Table 1 Variations in EC of the irrigation water during 3 years

Irrigation water	2008		2009		2010	
	Saline	Fresh	Saline	Fresh	Saline	Fresh
EC (dS/m)	4.04–4.86	1.21–1.64	3.35–3.78	0.94–1.17	3.68–3.77	1.14–1.27

Table 2 Quantities of irrigation water applied at different growth stages

Stages	Seeding	Budding	Early flowering-belling	Late flowering-belling	Boll opening	Total
Water quantity (%)	4.5	13.6	42.8	34.5	4.6	100
Water quantity (m³/ha)	187	570	1,800	1,448	195	4,200

Table 3 Deficit irrigation programs

	Stages	Seeding	Budding	Early flowering-belling	Late flowering-belling	Boll opening
	Irrigation #	1–2	3–5	6–10	11–16	17–18
Deficit irrigation (%)	D1	**70**[a]	100	100	100	100
	D2	100[b]	**70**	100	100	100
	D3	100	100	**70**	100	100
	D4	100	100	100	**70**	100

[a] 70 % irrigation water quantity in Table 2, [b] 100 % irrigation water quantity in Table 2

Table 4 Alternative irrigation programs

	Stages	Seeding	Budding	Early flowering-belling	Late flowering-belling	Boll opening
	Irrigation #	1–2	3–5	6–10	11–16	17–18
Control	F	F[a]	F	F	F	F
	S	S[b]	S	S	S	S
Alternative irrigation	A1	F	S	S	S	S
	A2	S	F	S	S	S
	A3	S	S	F	S	S
	A4	S	S	S	F	S

[a] Freshwater irrigation, [b] saline water irrigation

3. *Alternative irrigation* (Table 4): Freshwater was used during one growth stage and saline water in the others. Alternative irrigation scenarios are denoted by the letter A.
4. *Flood irrigation* with freshwater was used after the harvest in the winter or the following spring. The total amount of irrigation water applied outside of the growing season was 2,250 m³/ha.

Following local practices, cotton seeds were sown in April every year and mulched with degradable plastic sheeting. Two irrigation lines were installed for each four rows of cotton as shown in Fig. 1. The distance between the irrigation lines was 70 cm, and between two cotton rows 20 cm. Drippers along each irrigation line were spaced 30 cm apart, while the cotton plants along each row were spaced 10 cm apart. The non-mulched area of bare soil was 40 cm wide. A total of 225 kg/ha of urea, 375 kg/ha of diammonium phosphate, 300 kg/ha of compound fertilizer with 45 % potassium sulfate, and 225 kg/ha of farm manure were applied before sowing. Additionally 75 kg/ha of urea was applied after the budding stage, and 45 kg/ha of urea after early flowering-belling.

Monitoring

Soil water contents at various depths were measured in situ using L520 Neutron Probe (Institute for Application of Atomic Energy, JAAS, Nanjing, China) and Stevens Hydra
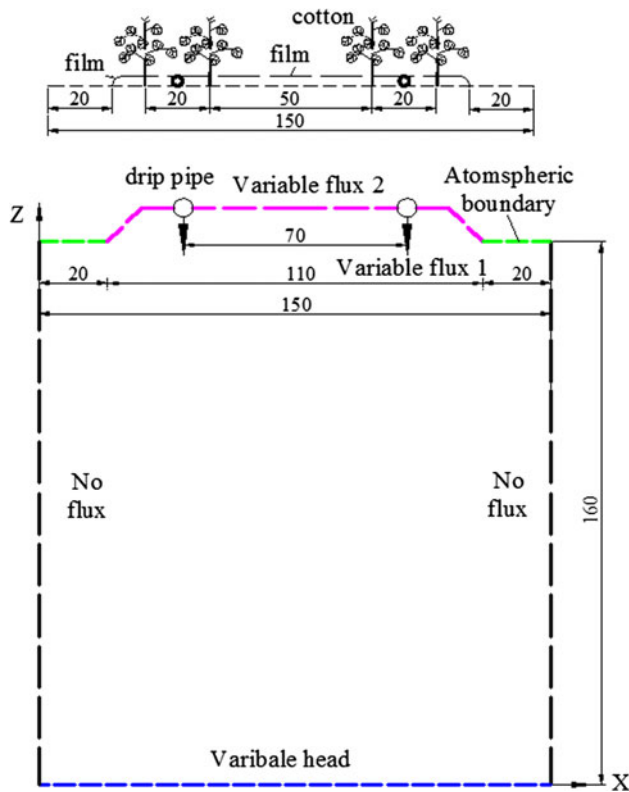
Fig. 1 Layout of cotton rows and drip irrigation lines in the field and the simulated transport domain. Also shown are boundary conditions used in the numerical analysis (distances are in cm)

Probe (*Stevens Water Monitoring Systems Inc.*, *Beaverton, OR, USA*) *soil sensors, while the top layer* was monitored using MP160 moisture probes (ICT International Pty Ltd., Armidale, Australia). The leaf area index (LAI) of cotton during the different growing season was measured with a WDY-500A Micro-electron Leaf Area Instrument (Harbin Optical Instrument Factory, Harbin, China). Final yields were measured for each treatment and each replicate. The field soil moisture capacity was measured after the basin irrigation treatments. Both fresh and saline waters were sampled before each irrigation. Soil solutions were extracted from different depths in the field using a Rhizon Soil Moisture Sampler (Eijkelkamp Agrisearch Equiment Co., Giesbeek, the Netherlands). Soils were sampled further for gravimetric water content measurements and to obtain 1–5 soil/water suspensions for EC analysis in the on-site laboratory. Chemical analyses (titrametric and atomic absorption spectrometry) were performed on the soil solutions and suspensions in the on-site laboratory. Measurements included EC, pH, and 8 major ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), except when only enough soil solution was available for the EC measurements. The EC of the 1–5 soil/water suspension is further referred to as $EC_{1:5}$.

Numerical model

In order to predict the long-term effects of the various irrigation management systems, the 2D module of the HYDRUS (2D/3D) software (Šimůnek et al. 2008, 2012) was selected for the simulations. We refer to the HYDRUS technical manual (Šimůnek et al. 2012) for a detailed description of the governing equations describing variably saturated flow using the Richards equation, solute transport using the advection–dispersion equation, and root water uptake, as well as of various initial and boundary conditions that can be implemented. Since the distance between drippers along a drip line was short compared to the other dimensions, the drip irrigation system was modeled as a line source. The two-dimensional transport domain used for the calculations is shown in Fig. 1. The depth of the transport domain was 160 cm and its width 150 cm. No-flow boundary conditions were considered along the two vertical sides of the transport domain. A time-variable pressure head specifying the position of the groundwater table was assigned along the bottom boundary.

The soil surface boundary conditions were relatively complicated since they had to accommodate two-dimensional surface drip irrigation, atmospheric conditions, the presence of cotton plants, and the presence of mulching plastic. Separate time-variable flux boundary conditions were used for the surface drip line and the soil surface under the mulch. The bare soil on the sides of the transport domain was represented using an atmospheric boundary condition. For solute transport, we used third-type Cauchy boundary conditions along all domain boundaries.

The water stress response model of Feddes et al. (1978) was used to account for water stress and the threshold-slope model of Maas and Hoffman (1977) for salinity stress. Parameters (Table 5) of the water and salinity stress response functions were based on the literature values (Taylor and Ashcroft 1972; Feddes et al. 1978; Maas 1990; Forkutsa et al. 2009). A multiplicative model was used to account for the combined effects of water and salinity stress (Skaggs et al. 2006). Compensated root water uptake (Šimůnek and Hopmans 2006) was not considered in our simulations since water and salinity stresses in the mulched system were assumed to be distributed relatively uniformly throughout the root zone. Cotton roots were sampled at a regular network of sampling points (Fig. 2a) and measured using DT-SCAN (Fig. 2b). The measured spatial root distribution is shown in Fig. 3. Since HYDRUS does not allow a time-variable root zone, a constant root distribution was assumed during the simulations. Plant growth was accounted for by modifying the ratio between evaporation (which dominated during the early growth stages) and transpiration (which dominated later).

Table 5 Estimated root water uptake parameters in the water stress response model of Feddes et al. (1978)

P0 (cm)	P0pt (cm)	P2H (cm)	P2L (cm)	P3 (cm)	r2H (cm/day)	r2L (cm/day)
−10	−25	−200	−600	−14,000	0.5	0.1

Fig. 2 **a** Layout of cotton root sampling and locations of drip irrigation lines in the field (distances are in cm), **b** root distribution measured using DT-SCAN
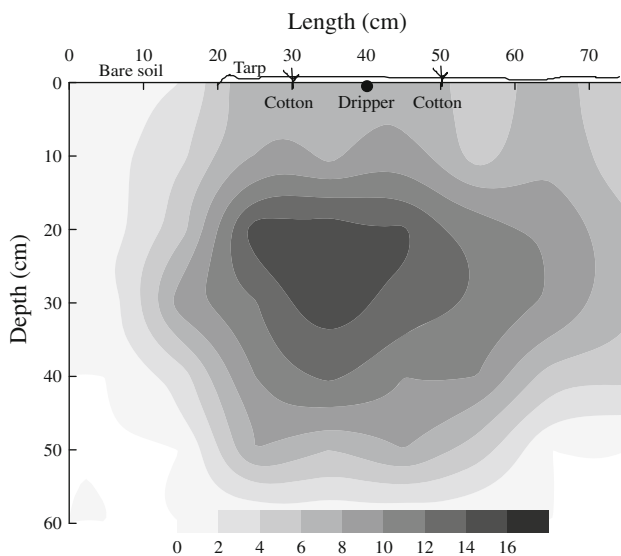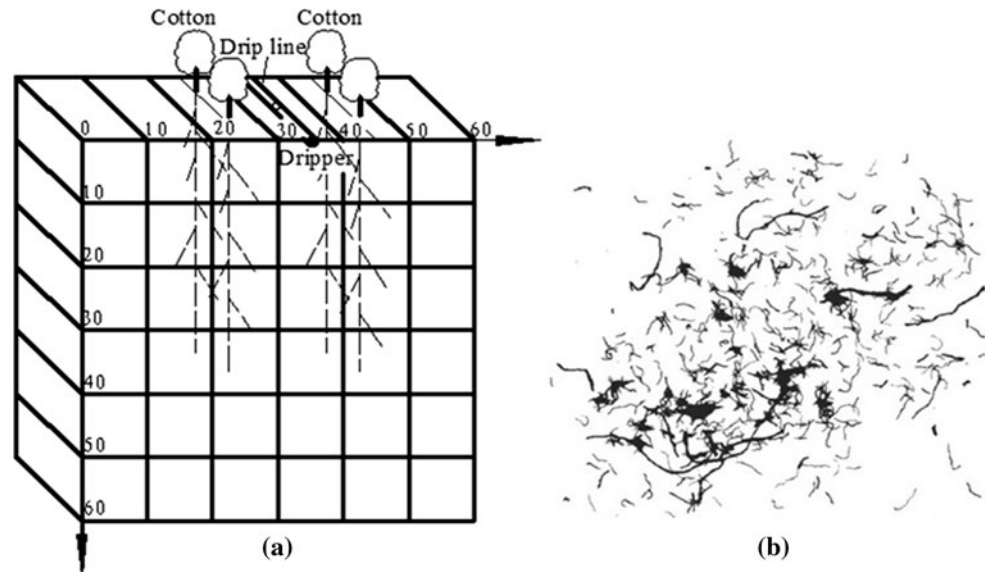
Fig. 3 Relative root distribution (mm/cm²)

Table 6 Soil hydraulic parameters used in the simulations

Soil	θ_r (−)	θ_s (−)	α (1/cm)	n (−)	K_s (cm/day)	l (−)
Loamy sand						
Initial parameters	0.054	0.400	0.036	1.56	35.3	0.5
Final parameters	0.054	0.400	0.022	2.06	35.3	0.5

The van Genuchten–Mualem model (van Genuchten 1980) was used to describe the soil hydraulic properties. Soil hydraulic parameters (Table 6) were estimated initially from a limited number of laboratory- and field-measured retention data points using the RETC program of van Genuchten et al. (1991). These and the solute transport parameters were subsequently adjusted manually such that the model predictions more closely matched observed soil water content and EC values of the profile below the dripper (Tables 6, 7).

The dynamics of EC in space and time was simulated as that of a non-reactive solute. As shown by Ramos et al. (2011), this approach can be used when the soil solution is undersaturated with respect to calcite and gypsum. In that case, almost identical results are obtained as simulations accounting for the transport of, and reactions between, major ions, such as can be done with the UnsatChem modules of HYDRUS (Šimůnek et al. 2008).

Results and discussion

Crop yields

Cotton yields and irrigation water productivities, IWPs (i.e., yields divided by the amount of applied irrigation water), are presented in Table 8. Results indicate that the average cotton yield during the 3 years varied from 3,575 to 5,095 kg/ha and the IWP from 0.91 to 1.16 kg/m³.

Table 7 Soil-specific parameters for solute transport

	Bulk density (g/cm^3)	Longitudinal dispersivity (cm)	Transverse dispersivity (cm)
Initial parameters	1.70	32	25.6
Final parameters	1.70	60	48

Cotton yields were on average highest in 2008, followed by 2010 and 2009, with the IWP following a similar trend. Both the average cotton yield (3,575 kg/ha) and the IWP (0.91 kg/m^3) were lowest for scenario D3 when deficit irrigation was used during early flowering-belling. The highest average IWP of 1.16 kg/m^3 was obtained for scenario D4 when deficit irrigation was used during late flowering-belling. Both the cotton yield and the IWP for scenario A3 were the second highest in 2009 and 2010, and the fourth highest (tied with scenario F) in 2008.

The average yield of 5,095 kg/ha was highest and the IWP of 1.13 kg/m^3 the second highest for scenario A1 when freshwater was used during the seedling growth stage. Both the average yield and IWP were higher for A1 than for control treatment F (freshwater during the entire growing season), for which the average yield was 4,555 kg/ha and the average IWP 1.01 kg/m^3. The average yield and IWP for scenario S (saline irrigation water) were 4,845 kg/ha and 1.08 kg/m^3, which were 6.4 and 6.9 % higher, respectively, as compared to control scenario. Also, both the average cotton yield and IWP for A3 and D4 were higher than for F. These results indicate slightly increased cotton growth when some salinity in the irrigation water is present. The yield-promoting effect of some soil salinity

has been reported in several studies (e.g., Qadir and Shams 1997; Ashraf and Ahmad 2000; Ashraf 2002; Henggeler 2004). For instance, Vulkan-Levy et al. (1998) found that with more water being applied, cotton yields increased with an increase in salinity. Hou et al. (2009) similarly showed that seed cotton yield, dry matter, and N uptake significantly increased as the soil salinity level increased from 2.5 to 6.3 dS/m.

Some of the increases in cotton yield may have been due also to higher concentrations of trace elements in saline water than in freshwater. Table 9 provides concentrations of trace elements in the irrigation water. Trace element concentrations (Cu, Fe, Mn, and Zn) in the saline water were much higher than in freshwater. Table 8 shows that the cotton yield and IWP decreased from 2008 to 2010. This was likely caused by a reduction in the concentrations of soil nutrients (Table 10) after 3 years of cultivation. These and other results are very much consistent with the fact that cotton is known to be the most sensitive to water and salinity stress during the seedling and early vegetative growth stages, and that cotton generally is more affected by water stress than salinity stress (e.g., Läuchli and Gratan 2007).

The yield and IWP variances for 3 years are also presented in Table 8. Both were lowest for scenario A3 when freshwater was used during early flowering-belling. The highest yield and IWP variances were obtained for scenario A2 when freshwater was used during the budding stage. The yield and IWP variances were both second lowest for scenario A1 when freshwater was used during seedling. The yield and IWP fluctuated only slightly for scenario A3, but strongly for scenario A2. The variability in cotton yield for the various scenarios increased as follows: A3 < A1 < D1 <

Table 8 Cotton yields and irrigation water productivities (IWP) for different treatments

Treatments	2008		2009		2010		Average		Variance	
	Yield (kg/ha)	IWP (kg/m^3)	Yield (kg/ha)	IWP (kg/m^3)	Yield (kg/ha)	IWP (kg/m^3)	Yield (kg/ha)	IWP (kg/m^3)	Yield (–)	IWP (–)
Controlled irrigation										
F	5,040	1.12	4,725	1.05	3,900	0.87	4,555	1.01	833	0.182
S	5,385	1.20	5,145	1.14	4,005	0.89	4,845	1.08	1,043	0.233
Deficit irrigation										
D1	4,545	1.02	3,900	0.88	3,765	0.85	4,070	0.92	590	0.128
D2	4,980	1.15	3,975	0.92	3,659	0.85	4,205	0.97	976	0.222
D3	4,500	1.15	3,195	0.81	3,031	0.77	3,575	0.91	1,138	0.295
D4	5,400	1.34	4,140	1.03	4,482	1.11	4,674	1.16	922	0.228
Alternative irrigation										
A1	5,190	1.15	4,665	1.04	5,430	1.21	5,095	1.13	553	0.122
A2	5,865	1.30	3,780	0.84	3,900	0.87	4,515	1.00	1,656	0.364
A3	5,040	1.12	4,725	1.05	4,815	1.07	4,860	1.08	230	0.051
A4	4,845	1.08	3,585	0.80	4,185	0.93	4,205	0.94	891	0.198

Table 9 Concentrations of trace elements in irrigation waters

Trace elements	Cu	Fe	Mn	Zn
Saline water (mg/L)	0.019–0.046	0.126–2.948	0.187–0.378	0.134–0.254
Freshwater (mg/L)	0.003–0.004	0.026–0.118	0.001–0.024	0.075–0.106

Table 10 Contents of soil nutrients before and after the experiments

Soil nutrients	N (mg/kg)	P (mg/kg)	K (mg/kg)
Before experiments	30.4	64.2	120.0
After 3 years	25.8	31.9	78.7

Table 11 Calculated crop sensitivity coefficients (Eq. 1) of cotton growth stages to irrigation water and salinity stress

	Seeding	Budding	Early flowering-belling	Late flowering-belling
Water stress	0.160	0.132	0.262	0.035
Salinity stress	0.052	0.068	0.003	0.132

F < A4 < D4 < D2 < S < D3 < A2 (see Tables 3, 4 for definitions). For IWP, the variability increased as A3 < A1 < D1 < F < A4 < D2 < D4 < S < D3 < A2.

The response of cotton to water and salt stress during the different growth stages was evaluated using a crop sensitivity coefficient (λ_i) defined as:

$$l_i = |Y_i - Y_C|/Y_C \tag{1}$$

where Y_i is the average yield for a particular treatment and Y_C is the average yield for the control treatment. Irrigation with saline water (S) was selected as the control scenario. Calculated sensitivities are given in Table 11. Crop sensitivities to water stress during the different growth stages were found to decrease as follows: early flowering-belling > seedling > budding > late flowering-belling. For salt stress, crop sensitivities decreased as follows: late flowering-belling > budding > seedling > early flowering-belling.

Spatial and temporal variability of soil salinity

Soil salinity levels may be evaluated using the electric conductivity of the saturation extract, EC_e, which can be estimated from measured values of $EC_{1:5}$. Slavich and Petterson (1993) reported the following relationship $EC_e = f \ EC_{1:5}$, where $f = 2.46 + 3.03/\theta_{sp}$, and θ_{sp} is the gravimetric water content of the saturated paste (kg/kg). For our experimental fields, the average θ_{sp} value was 0.20 kg/kg, which suggests that the value of f should be about 17.61 if the relationship of Slavich (1993) is used. For this reason, we related EC_e and $EC_{1:5}$ in this study using $EC_e = 17.61 \ EC_{1:5}$. Our own measurements of EC_e and $EC_{1:5}$ showed a very similar correlation (results not further reported here).

Figure 4 shows the temporal variability of EC_e in the soil root zone for the different treatments. The EC_e increased during the growing seasons for all treatments. However, EC_e for scenario S increased substantially, but increased only slightly for control scenario F. EC_e values continued to increase even when irrigation was terminated

after the growing season. This was caused by the high evaporation rate and the presence of saline groundwater with total dissolved solids (TDS) near 3 g/L. The concentrations of major cations and SAR of groundwater samples collected at different times are presented in Table 12. The various measurements indicate that a drainage system is needed. EC_e decreased dramatically after flood irrigation and then increased slightly before the next cultivation.

Figure 5 shows the water table depth versus time during the entire experiment (2.5 years). The water table during the growing season was higher than between two growing seasons. Irrigation caused a rise in the water table, even in the presence of drainage canals.

As discussed in section "Crop yields," the early flowering-belling and seeding growth stages were the most sensitive to water stress, whereas the late flowering-belling growth stage was the most susceptible to salinity stress. The budding and seedling stages were sensitive to salinity as well. According to the variance, the two most stable yields and IWPs were obtained for scenarios A3 and A1 when freshwater was used during the early flowering-belling and seedling growth stages. Therefore, our experimental results indicate that an alternative irrigation scenario would produce optimal yield. In this irrigation scenario, freshwater would be used during the seedling and early flowering-belling stages, and more saline water during the other growth stages. Additionally, flood irrigation should be applied after harvesting or before sowing. This scenario will be analyzed further in section "Long-term HYDRUS simulations" using long-term simulations.

Irrigation with saline water during the growing season caused an increase in salinity of the root zone. Since less water was used for individual irrigation events as compared to post-season flood irrigation, and salts hence were not leached below the root zone and into groundwater, the soil salinity in the root zone exceeded the threshold salinity value of 7.7 dS/m for cotton (Maas and Hoffman 1977) for
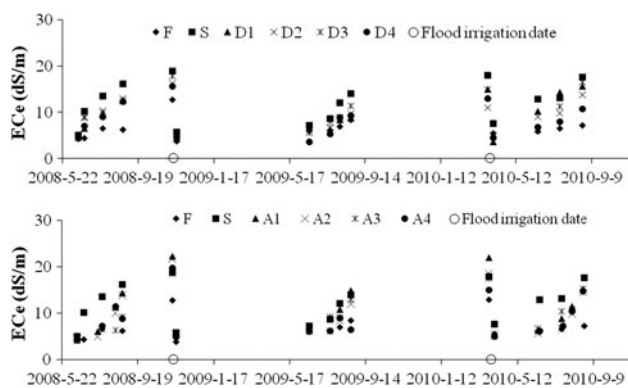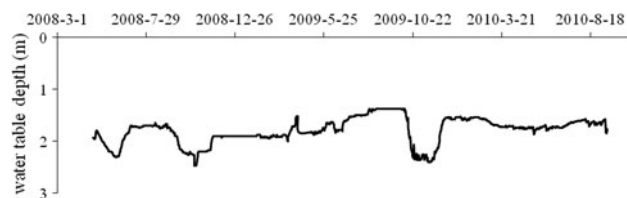
Fig. 4 Temporal variability of EC$_e$ in the root zone for different treatments

Fig. 5 Observed water table depth during the 3-year experiment

all treatments, except for treatment F during the later growth stages. If salinity was the only factor affecting yield, the maximum yield would be achieved for scenario F. However, cotton yields were likely affected not only by the quantity of irrigation water and its salinity, but also by nutrients dissolved in the irrigation water and present in the soil. Nutrient concentrations in the soil decreased, resulting in lower cotton yields, even though fertilization was the same every year. While salts in irrigation water can reduce the growth of cotton, trace elements to certain levels may enhance growth. We did not, as part of this study, analyze which trace elements and at what concentrations may have affected or limited cotton growth. As pointed out by Yermiyahu et al. (2008), the synergistic or antagonistic effects between salinity and trace elements are still not well understood.

HYDRUS model calibration

Figure 6 shows observed and calculated water content distributions at various depths below the drip line for irrigation scenario S, while similar plots for salinity are given in Fig. 7. The HYDRUS simulation results were obtained using the adjusted soil hydraulic parameters listed in Table 6. Figure 6 shows a generally good agreement between observed and calculated water contents, except perhaps at the 10- and 20-cm depths where simulated values showed much more variation versus time in response to irrigation than the observed values. This was mostly due to the relative long intervals between the field

water content measurements. The simulated values actually matched observed values quite well between days 50 and 80 when more measurements were taken. Only a relatively few observations did not match the simulated curves well during the entire growing season (notably the measurements deeper in the profile at approximately days 38 and 40).
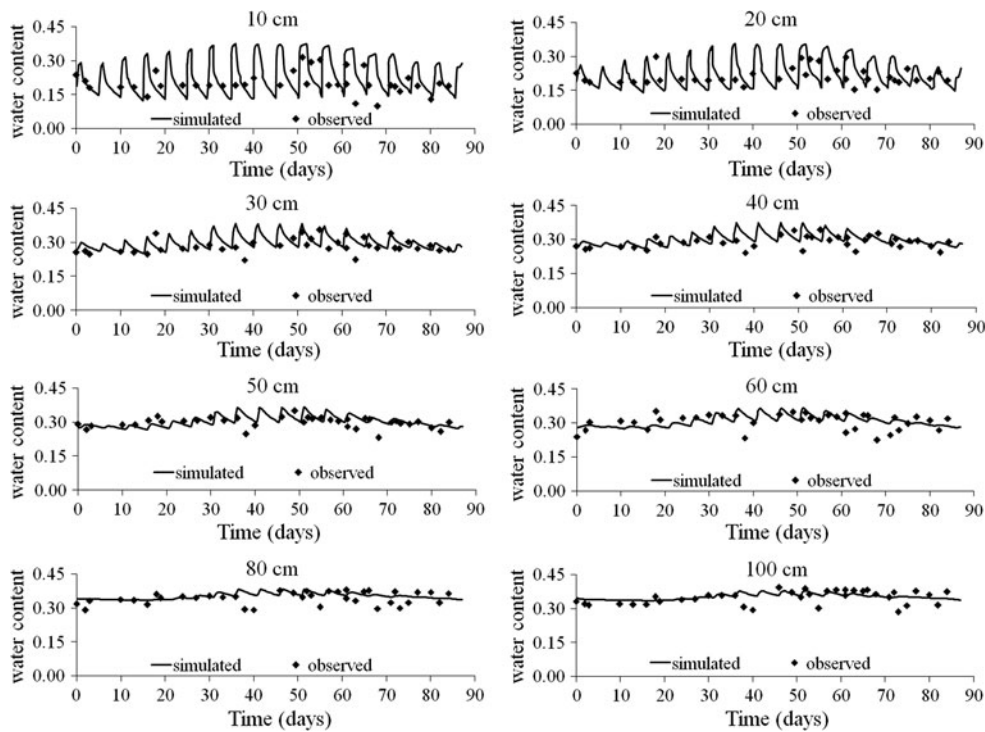
Observed and simulated EC values of soil water showed very similar variations during the 2008 growing season. The EC decreased slightly over time in the top 40-cm soil layer due to the leaching effect of irrigation by the dripper. This was also the main reason that EC values increased slightly below a depth of 80 cm. Very similar results in terms of observed versus calculated water contents (Fig. 6) and salinities (Fig. 7) were obtained for the other growing seasons of scenario S, as well as for the other irrigation scenarios, and are not further shown here. We conclude that, overall, simulated values of the soil water content and the EC matched the observed values well.

Long-term HYDRUS simulations

An important objective of this study was to obtain a clear understanding of the long-term effects of the various irrigation scenarios on possible salt accumulation and sustainable cotton production. The HYDRUS software package was used for this purpose to extend the simulation period by 20 years. To do so, we simply repeated the available 10 years of meteorological data twice to provide the necessary boundary conditions for the 20-year simulations. We used for the extended simulations the same spatial root distribution for cotton and the same soil hydraulic and solute transport parameters as used for the simulations shown in Figs. 6 and 7. Measured soil water contents and ECs before sowing in 2011 were used as initial conditions. We considered three irrigation scenarios: (a) mulched drip irrigation with freshwater (FI),

Table 12 Ion concentrations in groundwater samples (units: g/L, except SAR)

Sampling date	Ca^{2+}	Mg^{2+}	K$^+$	Na$^+$	CO$_3^{2-}$	HCO$_3^-$	Cl$^-$	SO$_4^{2-}$	TDS	SAR
03 July 2009	0.276	0.097	0.058	0.226	0.001	0.414	0.442	0.672	2.186	4.201
15 July 2009	0.326	0.050	0.057	0.396	0.001	0.414	0.489	0.893	2.626	7.612
20 March 2010	0.278	0.145	0.029	0.416	0.001	0.324	0.442	1.301	2.936	7.097

Fig. 6 Observed and simulated soil volumetric water contents at different depths under the drip line for scenario S
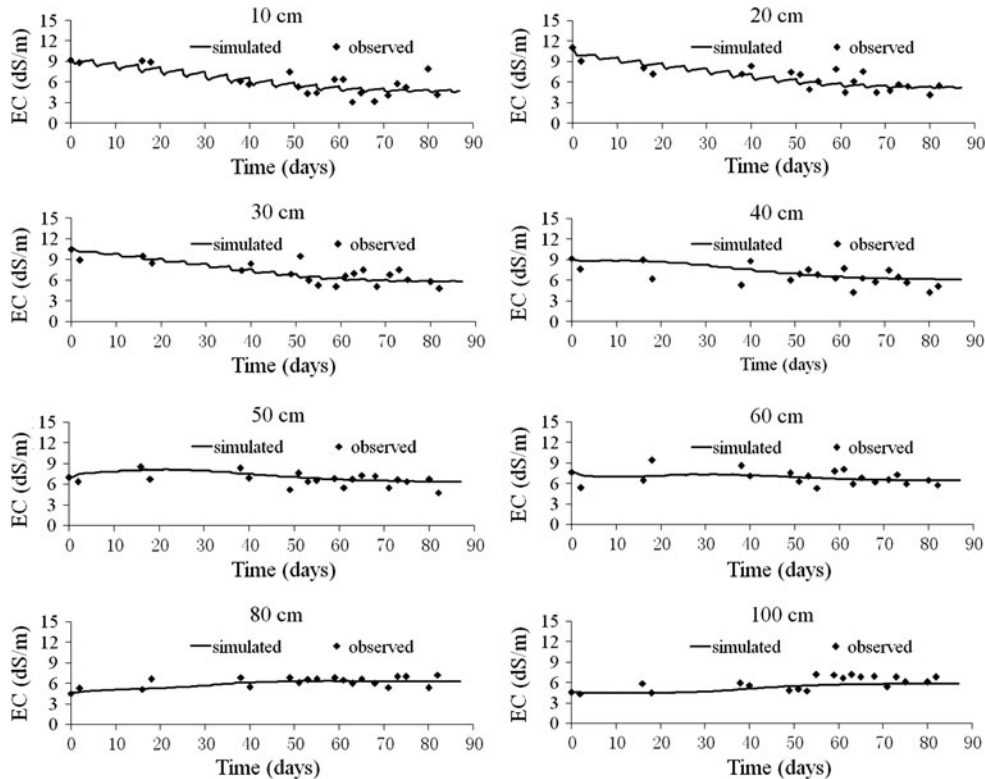
Fig. 7 Observed and simulated soil water EC values at different depths under the drip line for scenario S

(b) mulched drip irrigation with saline water (SI), and (c) mulched drip irrigation with the alternative use of fresh and saline water (AI). For the AI scenario, freshwater was used for irrigation during seedling and the early flowering-belling stages, and saline water during the other growth stages, as described in section "Spatial and temporal

variability of soil salinity." Post-season flood irrigation with freshwater was considered for all three scenarios.

The simulation results are shown in Fig. 8. For all three scenarios (FI, SI, and AI), variations in the EC of soil water were very similar between the different years, except that EC values decreased slightly year after year. While EC of the top 30-cm soil layer varied markedly, little variations were observed below a depth of 40 cm. For scenario SI (drip irrigation with saline water), the EC of soil water first increased slightly during the growing season, but then more substantially after harvesting until flood irrigation. Flood irrigation subsequently caused the EC to decrease, which then remained more or less constant until the next growing season. These fluctuations reflect mainly variations in the soil water content during the year.

The EC of soil water during the growing seasons did not change much because of the relatively high soil water content due to irrigation. When irrigation was terminated after the growing season, the decreasing water content due to evaporation and some continuing transpiration caused the EC to increase. Subsequent flood irrigation caused most salts to leach below the root zone, thus allowing the EC to decrease again to background levels. EC variations for the FI and AI scenarios were similar as for SI, except that the EC fluctuations were more pronounced for FI and AI. The EC values for these two scenarios were also always lower than for scenario SI.

The HYDRUS simulation results showed that none of the three assumed irrigation scenarios (i.e., FI, SI, and AI) would result in soil salinization during the next 20 years. This indicates that the use of the mulched drip irrigation during the growing season, followed by flood irrigation with freshwater in the post-harvest season, is a feasible and sustainable irrigation strategy, provided that leaching is not limited by other factors such as a high water table. The literature suggests that the salinity tolerance threshold of cotton is about 7.7 dS/m (Maas and Hoffman 1977). However, analyses of field experiments with the alternative

Fig. 8 Simulated soil water EC values during 20 years for the FI (*top*), SI (*middle*), and AI (*bottom*) irrigation regimes, in combination with post-season leaching using 2,250 m³/ha of freshwater
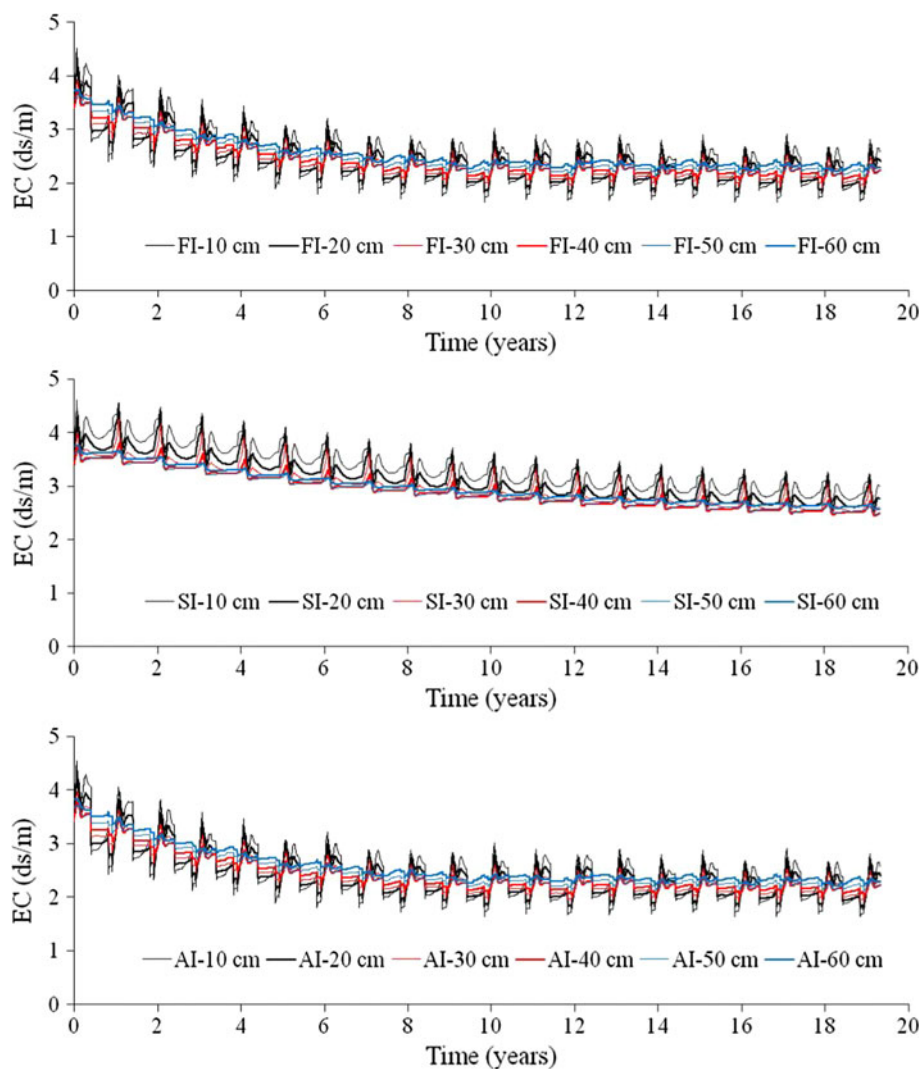
Fig. 9 Simulated soil water EC values during 20 years for scenario FI without post-season leaching
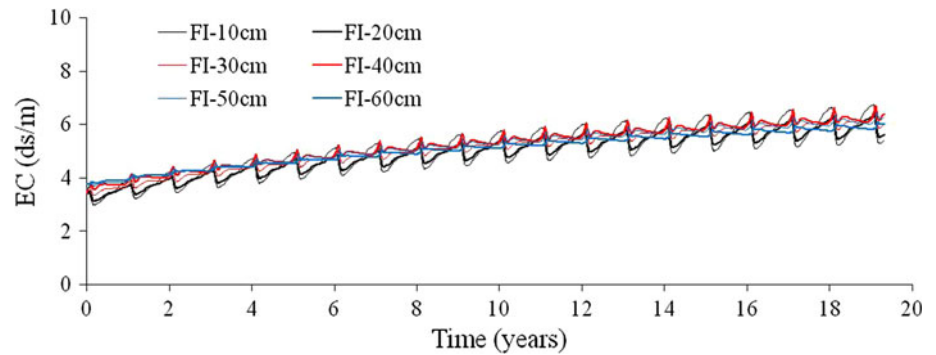
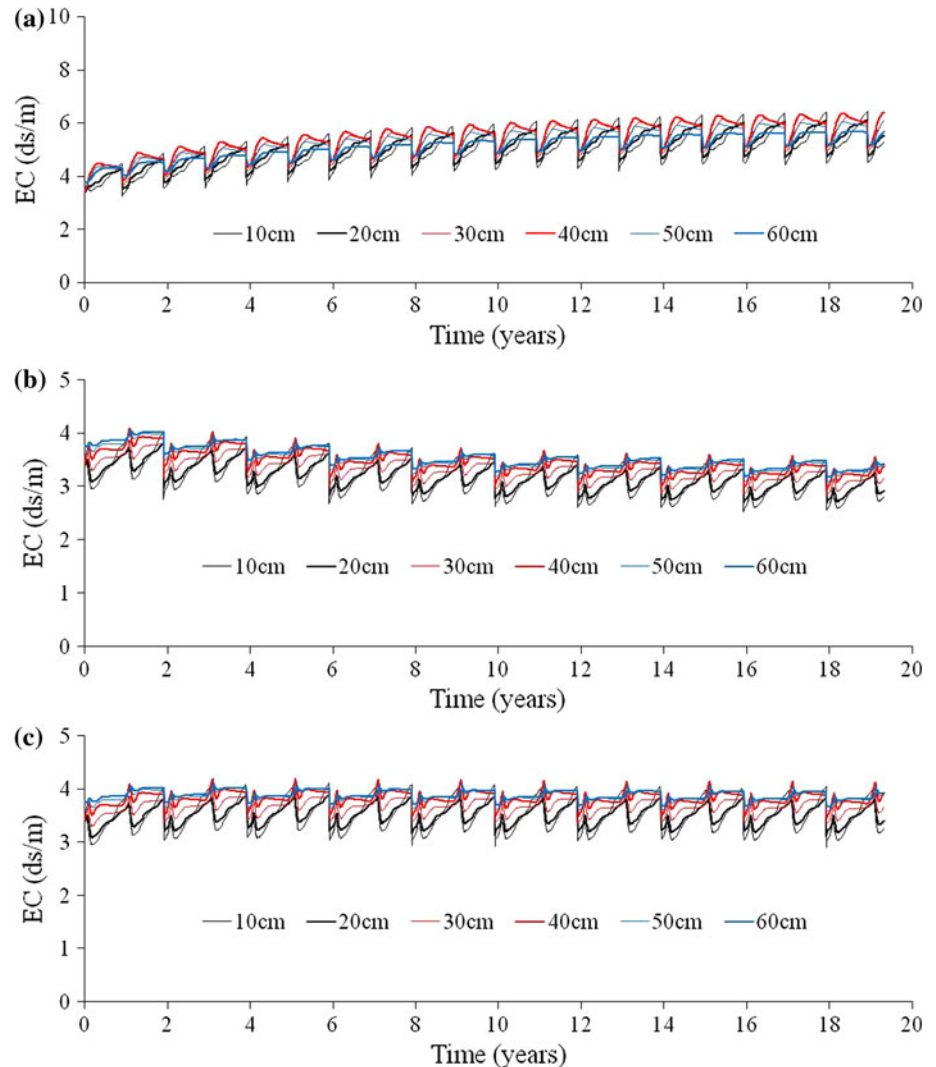**Fig. 10** Simulated soil water EC values during 20 years for the SI and AI irrigation scenarios assuming different post-season leaching options: **a** SI + annual leaching (1,575 m³/ha), **b** AI + biennial leaching (2,250 m³/ha), and **c** AI + biennial leaching (1,575 m³/ha)

use of fresh and saline waters indicate that different cotton growth stages have different sensitivities to salinity. Several studies (e.g., Beltran 1999; Murtaza et al. 2006; Zheng et al. 2009) have shown that cotton growth may be affected already by EC_e values close to 3 dS/m. Therefore, alternative irrigation schemes such as scenario AI in our study may well be sustainable for irrigating cotton in arid areas

experiencing a general shortage of freshwater resources, but with modestly saline water available.

Because of the shortage of freshwater supplies in the study area and based on the simulation results presented above (which indicated that it may be possible to reduce post-season leaching), we considered additional scenarios in which post-season leaching was either eliminated

altogether, or where the leaching frequency or water quantity was adjusted.

Three scenarios (i.e., FI, SI, and AI) without post-season leaching were considered first. All three irrigation scenarios without post-season leaching were found to lead to salinization over the 20-year simulation period. The results for scenario FI, presented in Fig. 9, indicate that EC gradually increased over time, even when freshwater was used for irrigation. Therefore, some leaching is recommended, even for the mulched drip irrigation scenario using freshwater (FI).

We additionally considered scenarios in which either the post-season leaching frequency was decreased (e.g., from once every year to once every 2 years), or the water quantity was reduced (e.g., from 2,250 to 1,575 m³/ha). Figure 10 shows the results for the scenario SI with annual post-season leaching using 1,575 m³/ha water, scenario AI with biannual post-season leaching using 2,250 m³/ha water, and scenario AI with biannual post-season leaching using 1,575 m³/ha water. Of the three options, both AI scenarios (with either annual or biannual leaching) did not lead to soil salinization over time, while scenario SI performed the worst. For these reasons, we recommend scenario AI, which uses freshwater during the early growth stages of cotton and saline water during the remaining growth stages, combined with post-season leaching every 2 years using 1,575 m³/ha of freshwater. Predictions show that this scenario is sustainable while using less freshwater.

Flood irrigation with freshwater could be adapted to match cotton growth stages based on soil salinity conditions and available freshwater resources. If soil salinity is close to or exceeds the threshold value during the growing season, flood irrigation could be applied. However, if freshwater is not immediately available or scarce at that time, leaching could be scheduled either earlier or later depending upon freshwater availability. Similarly, drip irrigation with freshwater could be continued longer than standard practice to promote some leaching of the salts out of soil root zone.

Freshwater is extremely scarce in some areas of Southern Xinjiang. For example, the total quantity of water available during the entire year in the middle and lower reaches of the Tarim River was only 3,000 m³/ha in 2010, while groundwater had a relatively high salinity of 4.6 dS/m. The engineering cost of water delivery may then be far too high to justify maximum yields (according to our investigation). Considering economic issues, the overall goal hence must be optimal yields (most yield per unit water), rather than maximum yields, so that the income of farmers is stable and their living conditions may improve. As such, there is also no absolute need to always keep soil salinities below the generally poorly defined salinity threshold value (van Genuchten and Gupta 1993; Steppuhn et al. 2005).

Conclusions

Our 3-year study showed that somewhat higher cotton yields and irrigation water productivities could be obtained using alternative scenarios A1 and A3 when freshwater is supplied only to the seeding and early flowering-belling growth stages, as compared to the control scenarios. The average cotton yield over the 3-year period was highest for scenario A1, while scenario D4 (deficit irrigation during late flowering-belling) produced the highest average IWP. Both the cotton yield and the IWP for scenario A3 were the second highest in 2009 and 2010, and the fourth highest in 2008. The yield was more stable for scenario A3 than for scenario A1 during the experiments. Different stages of cotton growth showed different responses to water and salinity stress. The early flowering-belling and budding stages were found to be more sensitive to water stress than other stages, while the late flowering-belling and seedling stages were more susceptible to salinity. However, we emphasize some caution in these conclusions since the variability in yield among the different treatments was found to be relatively high. This suggests that it would be beneficial to carry out a few selected long-term experiments for some of the more promising scenarios.

Long-term numerical simulations were performed for three irrigation scenarios (FI, SI, and AI). Results showed that soil water EC variations were similar in different years, and that EC values gradually decreased over time for all scenarios involving annual post-season leaching using 2,250 m³/ha of freshwater. This indicates that irrigation scenarios consisting of mulched drip irrigation during the growing season and flood irrigation in the post-season would not lead to soil salinization. Post-season leaching is recommended even for mulched drip irrigation with freshwater (scenario FI). Simulation results for the AI scenarios indicate that sustainable irrigation of cotton can be achieved when freshwater is used during the early growth stage of cotton and saline water during the remaining growth stages, in combination with post-season leaching every 2 years using 1,575 m³/ha of freshwater.

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