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Root-Zone Salt Retention Links Brackish Water Salinity and Irrigation Quota to Yield of Mulched Drip-Irrigated Cotton in Northern Xinjiang

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Abstract

Brackish water use is usually judged by water salinity, yet under drip irrigation cotton responds to the salt retained in the root zone. A two-season (2024–2025) randomized block experiment on the northern slope of the Tianshan Mountains combined three water salinities (0.9, 4.0 and 7.0 dS m^{-1}) and two quotas (100% and 75%) under mulched drip irrigation to test whether root-zone salt retention links water salinity and quota to yield, and whether lower N_2O emissions under saline irrigation reflect cleaner production or a smaller crop. At full quota, salt stored in the 0–100 cm profile increased by 2.0 (fresh water) to 18.0 t ha^{-1} (7.0 dS m^{-1}) per season, and, per ton of salt applied, storage change was larger under the 75% quota (1.05 versus 0.84 t). Compared with fresh water at full quota, yield was 3.0% lower at 4.0 dS m^{-1} (not significant) and 8.2% lower at 7.0 dS m^{-1}, and 24.4% lower at 7.0 dS m^{-1} with the 75% quota. Relative yield fell by 3.3% (95% CI 0.8–5.7%) and 5.8% (3.2–8.3%) per 1 dS m^{-1} increase in seasonal root-zone ECe at the full and 75% quotas. Cumulative N_2O fell by up to 41%, but yield-scaled N_2O (N_2O-N per ton of seed cotton) did not differ significantly. Over the two seasons at this site, water near 4 dS m^{-1} was compatible with full-quota irrigation followed by fresh-water winter irrigation; higher salinity combined with deficit irrigation was not.

Keywords: saline water irrigation; mulched drip irrigation; root-zone salinity; salt balance; leaching fraction; irrigation quota; cotton; N_2O emissions

1. Introduction

Irrigated agriculture in arid regions increasingly depends on scarce and often saline water, and soil salinity remains a major unresolved constraint on its productivity [1,2]. Brackish water can relieve pressure on fresh water only if the salt it carries does not accumulate in the root zone faster than it is removed. Crop responses to salinity follow an osmotic phase and an ion-injury phase [3] and alter evapotranspiration and irrigation requirements [4]. In practice, a threshold–slope relation between yield and the seasonal mean electrical conductivity of the saturation extract (ECe) is combined with irrigation-water classes based on the electrical conductivity of the water [5,6]; composite irrigation water quality indices add sodicity and specific-ion hazards [7,8], but they still classify the water rather than the soil that receives it. Under mulched drip irrigation, farmers choose both the water quality and the quota, and the two choices interact through the salt balance of a small wetted volume.

Drip irrigation changes where the salt goes. It wets only part of the soil, so a low-salinity zone forms around emitters while salt is pushed to the margins of the wetted

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volume and into unirrigated soil [9], and root water uptake follows the salinity of the wetted zone [10]. Field studies on cotton in northwest China have examined yield-compatible water salinities [11], water–salt thresholds [12], fifteen years of saline irrigation under film [13], and combinations of irrigation amount and salinity [14]. Fresh-water leaching at selected growth stages can offset salt delivered by brackish water [15], and water–salt balances of typical mulched-drip schedules have been quantified in northern Xinjiang [16]. Long-term water-saving practices can sustain yield on reclaimed saline-alkali land [17], and smart irrigation that regulates root-zone water and salinity can balance economic and environmental outcomes [18].

Two matters remain unresolved. First, guidelines and most experiments are organized around the salinity of the water, whereas the soil retains only part of the salt it receives. How large that part is, and what governs it, is rarely reported because salt mass balances are seldom closed alongside yield. Deficit irrigation illustrates the problem. It delivers less salt but also leaches less of it; in orchard systems the rise in root-zone salinity varies inversely with the leaching fraction [19], and steady-state leaching requirements can misjudge transient conditions [20]. Field evidence on whether a smaller quota mitigates or compounds salt stress in cotton is inconsistent [14]. Second, environmental outcomes are seldom measured on the same plots. Nitrous oxide (N_2O) production depends on water-filled pore space [21,22], salinity alters soil nitrogen pools and fluxes [23], and water quality changes the use of fertilizer nitrogen under mulched drip irrigation [24]. It is unknown whether lower emissions under saline irrigation reflect a cleaner system or merely a smaller crop.

As fresh-water allocations tighten, the practical question is no longer whether brackish water can be used but at what quota and for how many seasons, and water-quality classes answer neither. These gaps point to a conceptual problem. If yield depends on the salt retained in the root zone rather than on the water that delivered it, the same water can be harmless under one quota and harmful under another, and harmless in the first season but harmful in the second. Water-quality classes express neither behavior, whereas root-zone ECe and the leaching fraction (LF) can. We tested three hypotheses:

H1. *Salt retained in the 0–100 cm profile increases with irrigation water salinity, and the retained share of applied salt is larger under a 75% quota than under the full quota because LF is smaller.*

H2. *Yield loss with increasing water salinity is transmitted through seasonal root-zone ECe, so that ECe explains yield once water salinity is controlled for, and yield declines more steeply with ECe under the 75% quota.*

H3. *Cumulative N_2O emission falls with root-zone ECe and with the 75% quota, but yield-scaled N_2O (N_2O-N emitted per unit of seed cotton yield) falls proportionally less because yield also declines.*

We tested these hypotheses in a two-season (2024–2025) randomized block experiment with mulched drip-irrigated cotton on the northern slope of the Tianshan Mountains, crossing three water salinities with two irrigation quotas. The objectives were to quantify the salt balance of each treatment (H1), to test whether root-zone ECe carries the yield response to water salinity and quota (H2), and to compare area-scaled (per hectare) and yield-scaled (per ton of seed cotton) N_2O (H3). Salt and water balances, profile salinity, yield components, water productivity and N_2O were measured on the same plots, so that the chain from salt delivery to yield and emissions could be examined in one data set. Two seasons allow statements about short-term responses and carry-over, not about long-term salinization.

2. Materials and Methods

2.1. Study Site and Soil

The experiment was conducted in 2024 and 2025 in an irrigated field near Shihezi on the northern slope of the Tianshan Mountains, at the southern margin of the Junggar Basin (about 44.3° N, 86.0° E; elevation about 450 m). The climate is temperate continental and arid, with an annual mean air temperature of about 6.5 °C, annual precipitation of roughly 200 mm and potential evaporation above 1000 mm. Precipitation during the crop season (25 April–5 October) was 118 mm in 2024 and 86 mm in 2025, reference evapotranspiration (ET_0) was 884 and 931 mm, and mean air temperature was 21.4 and 22.0 °C (Figure 1). June–August was hotter in 2025 than in 2024 (daily maximum above 35 °C on 15 days in 2025 and on none in 2024; mean ET_0 6.4 versus 6.0 mm d^{-1}), with similar precipitation in that period (46 and 51 mm). The soil is an irrigated gray desert soil (Aridisol) of loam texture (sand 38%, silt 44%, clay 18% in 0–60 cm), with bulk density increasing from 1.40 g cm^{-3} at 0–20 cm to 1.51 g cm^{-3} at 80–100 cm, pH (1:5) of 8.1 and soil organic carbon of 10.4 g kg^{-1}. The groundwater table remained below 4.5 m, so capillary rise was neglected. Before the first season, ECe in the in-film zone averaged 3.2 dS m^{-1} over 0–60 cm (2.5–3.8 dS m^{-1} by layer), which is slightly saline (2–4 dS m^{-1}) in the USDA classification [25], whereas the surface 0–20 cm of the bare inter-film strip reached 8.6 dS m^{-1}. Salt storage in 0–100 cm was 13.2 ± 1.6 t ha^{-1} (mean ± SD, n = 24 plots).

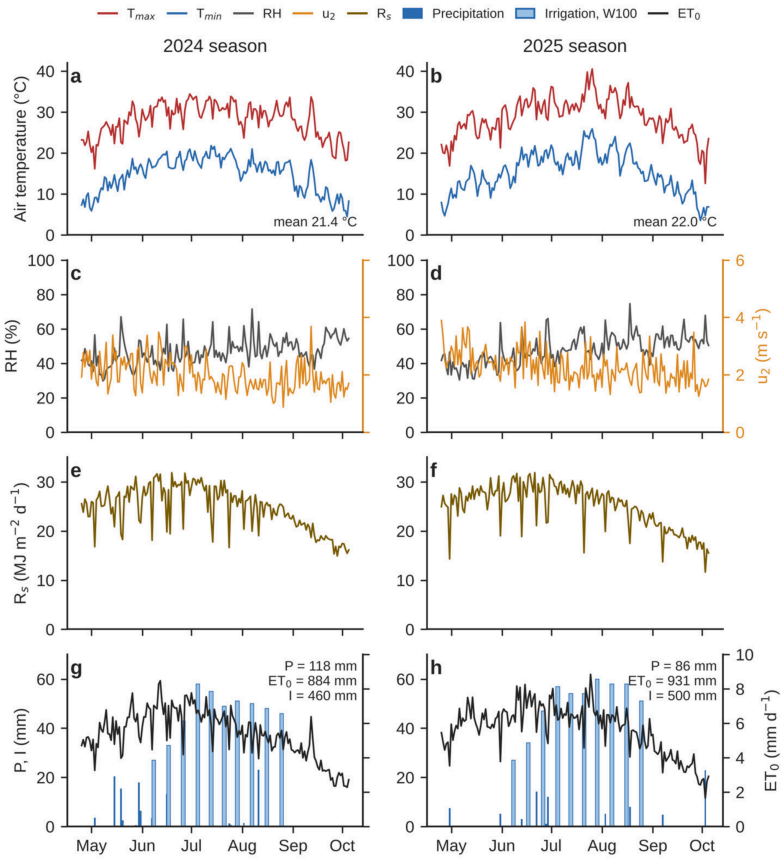


Figure 1. Daily weather at the experimental site in the (**a**,**c**,**e**,**g**) 2024 and (**b**,**d**,**f**,**h**) 2025 seasons (25 April–5 October): (**a**,**b**) maximum (T_{max}) and minimum (T_{min}) air temperature; (**c**,**d**) mean relative humidity (RH) and wind speed at 2 m (u_2); (**e**,**f**) solar radiation (R_s); (**g**,**h**) precipitation, irrigation depth of the full-quota treatment (W100) on each date and reference evapotranspiration (ET_0) calculated with the FAO-56 Penman–Monteith equation. W75 received 75% of each W100 depth on the same dates.

2.2. Experimental Design and Management

Treatments combined three irrigation water salinities (S1, S4 and S7, with nominal electrical conductivities of 0.9, 4.0 and 7.0 dS m^{-1}) and two quotas (W100, the full quota, and W75, 75% of W100) in a randomized complete block design with four blocks, giving six treatments and 24 plots (Table 1). Plots measured 4.1 m × 12 m (two films, 49.2 m^2) and were separated by 1.5 m buffers. The same plots were used in both seasons without re-randomization. Brackish and saline waters were prepared by blending canal water (0.9 dS m^{-1}) with saline groundwater in a mixing tank, and electrical conductivity was checked at every irrigation with a portable meter. W100 was set as the net crop water requirement, estimated from FAO-56 ET_0 and a crop coefficient for mulched drip-irrigated cotton [26,27], plus a leaching allowance of about 10%. Crop evapotranspiration was calculated as $ET_c = K_c \times ET_0$ from daily ET_0 (Section 2.3), with K_c of 0.23 until 31 May, rising linearly to 0.88 by 5 July, constant until 20 August and declining linearly to 0.44 by 5 October. These are the eddy covariance values for mulched drip-irrigated cotton in an arid oasis of northwest China [27], close to the basal coefficients of 0.20, 0.90 and 0.50 derived for the same system [28], and the stage construction follows FAO-56 [26]. The seasonal requirement was the sum of ET_c minus effective precipitation (80% of events ≥ 5 mm) between 25 May and 15 September, multiplied by 1.10, and it was divided among the irrigation events in proportion to the ET_c accumulated since the previous event. It amounted to 460 mm in 2024 and 500 mm in 2025, applied in ten irrigations between 8 June and 25 August (27–60 mm per event; Figure 1g,h), and W75 received 345 and 375 mm in the same ten events. All plots also received an identical 30 mm fresh-water emergence irrigation and, after the 2024 harvest, an identical 200 mm fresh-water winter irrigation.

Table 1. Treatments, irrigation water salinity, seasonal irrigation, salt applied with the irrigation water, and drainage below 100 cm and its estimated salinity in each season.

Treatment	Season	EC of Water (dS m^{-1})	Irrigation (mm)	Salt Applied (t ha^{-1})	D (mm)	EC_{dr} (dS m^{-1})
S1W100	2024	0.9	460	2.7	27.8 ± 9.1	6.9 ± 0.1
	2025	0.9	500	2.8	24.7 ± 5.0	6.4 ± 0.4
S1W75	2024	0.9	345	2.0	13.7 ± 6.4	6.6 ± 0.1
	2025	0.9	375	2.1	12.2 ± 6.2	6.0 ± 0.1
S4W100	2024	4.1	460	11.9	34.9 ± 10.7	9.2 ± 0.3
	2025	3.9	500	12.6	31.1 ± 3.1	11.6 ± 0.2
S4W75	2024	4.0	345	8.9	10.2 ± 4.2	8.2 ± 0.2
	2025	4.0	375	9.5	9.1 ± 4.7	10.0 ± 0.2
S7W100	2024	6.8	460	20.0	55.2 ± 15.2	10.5 ± 0.1
	2025	7.2	500	23.0	49.1 ± 11.1	16.2 ± 0.5
S7W75	2024	6.9	345	15.2	17.5 ± 7.3	9.4 ± 0.2
	2025	7.1	375	17.1	15.5 ± 8.9	13.3 ± 0.3

Salt applied = irrigation volume × total dissolved solids of the water (0.64 kg m^{-3} per dS m^{-1}). All treatments received 240 kg N ha^{-1}. D, drainage below 100 cm from Darcy fluxes (Section 2.3); EC_{dr}, salinity of the drainage water estimated as $2 \times ECe_{80–100}$ (Section 2.5). D and EC_{dr} are means ± SE (n = 4 plots); LF = D / I is given in Table 2.

Cotton (*Gossypium hirsutum* L., an early-maturing upland cultivar widely grown in northern Xinjiang) was sown on 25 April under 0.01 mm polyethylene film in a 1 film–3 drip tapes–6 rows pattern (66 + 10 cm wide–narrow rows, 10 cm plant spacing, target density 2.4×10^5 plants ha^{-1}). Drip tapes had emitters every 30 cm (2.0 L h^{-1} at 0.1 MPa), and each plot had a water meter. All plots received 240 kg N ha^{-1} as urea through the drip system in eight equal fertigations of 30 kg N ha^{-1} (day of year 161–233), together with

90 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} as basal fertilizer. Seed cotton was hand-picked between 28 September and 3 October.

Table 2. Water and salt balance and seasonal root-zone salinity of the six treatments in each season and over both seasons (mean ± SE, n = 4 plots, with F values from two-way and split-plot analysis of variance).

Treatment	ET_a (mm)	LF (%)	S_{out} (t ha^{-1})	ΔSS (t ha^{-1})	R	ECe_{rz} (dS m^{-1})
2024 season						
S1W100	544 ± 1 a	6.1 ± 2.0 ab	1.23 ± 0.40 b	1.6 ± 0.7 c	0.55 ± 0.15 b	3.42 ± 0.23 bc
S1W75	489 ± 5 b	4.0 ± 1.9 b	0.58 ± 0.28 b	1.2 ± 0.2 c	0.71 ± 0.14 ab	3.17 ± 0.09 c
S4W100	541 ± 4 a	7.6 ± 2.3 ab	2.07 ± 0.64 ab	10.6 ± 1.2 b	0.83 ± 0.05 ab	4.43 ± 0.23 a
S4W75	483 ± 7 b	3.0 ± 1.2 b	0.54 ± 0.23 b	8.4 ± 0.7 b	0.94 ± 0.03 a	4.11 ± 0.19 ab
S7W100	536 ± 5 a	12.0 ± 3.3 a	3.70 ± 1.02 a	17.2 ± 0.6 a	0.81 ± 0.05 ab	4.62 ± 0.43 a
S7W75	490 ± 8 b	5.1 ± 2.1 ab	1.05 ± 0.44 b	15.5 ± 0.8 a	0.93 ± 0.03 a	4.91 ± 0.31 a
F values, two-way ANOVA, 2024						
Salinity (S)	0.52 ns	3.1 ns	5.9 *	286 ***	6.6 **	28.2 ***
Quota (Q)	196 ***	12.7 **	19.8 ***	7.8 *	4.2 ns	0.39 ns
S × Q	0.91 ns	1.2 ns	2.6 ns	1.1 ns	0.07 ns	1.4 ns
2025 season						
S1W100	570 ± 1 a	4.9 ± 1.0 ab	1.01 ± 0.21 b	2.5 ± 0.6 c	0.64 ± 0.08 b	3.04 ± 0.21 c
S1W75	511 ± 3 b	3.2 ± 1.6 ab	0.46 ± 0.23 b	2.0 ± 0.2 c	0.78 ± 0.11 ab	3.01 ± 0.35 c
S4W100	567 ± 4 a	6.2 ± 0.6 ab	2.31 ± 0.22 b	9.2 ± 0.1 b	0.82 ± 0.02 ab	4.65 ± 0.25 b
S4W75	505 ± 3 b	2.4 ± 1.2 b	0.58 ± 0.30 b	9.2 ± 0.5 b	0.94 ± 0.03 a	4.63 ± 0.15 b
S7W100	562 ± 5 a	9.8 ± 2.2 a	5.08 ± 1.15 a	18.8 ± 0.5 a	0.78 ± 0.05 ab	6.16 ± 0.06 a
S7W75	488 ± 2 c	4.1 ± 2.4 ab	1.33 ± 0.75 b	17.1 ± 0.6 a	0.92 ± 0.04 a	6.15 ± 0.40 a
F values, two-way ANOVA, 2025						
Salinity (S)	11.5 ***	2.2 ns	9.5 **	616 ***	5.6 *	83.4 ***
Quota (Q)	575 ***	8.9 **	17.9 ***	3.7 ns	9.4 **	0.07 ns
S × Q	2.9 ns	0.84 ns	3.9 *	2.0 ns	0.02 ns	0.03 ns
Mean of 2024 and 2025						
S1W100	557 ± 1 a	5.5 ± 1.1 ab	1.12 ± 0.20 b	2.0 ± 0.6 c	0.59 ± 0.07 b	3.23 ± 0.22 c
S1W75	500 ± 3 b	3.6 ± 1.7 b	0.52 ± 0.25 b	1.6 ± 0.2 c	0.75 ± 0.12 ab	3.09 ± 0.13 c
S4W100	554 ± 4 a	6.9 ± 1.4 ab	2.19 ± 0.38 b	9.9 ± 0.6 b	0.82 ± 0.03 ab	4.54 ± 0.24 b
S4W75	494 ± 4 b	2.7 ± 1.1 b	0.56 ± 0.23 b	8.8 ± 0.5 b	0.94 ± 0.03 a	4.37 ± 0.17 b
S7W100	549 ± 5 a	10.9 ± 2.6 a	4.39 ± 1.05 a	18.0 ± 0.5 a	0.79 ± 0.05 ab	5.39 ± 0.24 a
S7W75	489 ± 3 b	4.6 ± 2.1 b	1.19 ± 0.50 b	16.3 ± 0.6 a	0.93 ± 0.03 a	5.53 ± 0.36 a
F values, split-plot ANOVA over both seasons						
Salinity (S)	4.0 *	3.7 ns	10.2 **	639 ***	8.6 **	131 ***
Quota (Q)	489 ***	15.2 **	24.3 ***	9.3 **	7.2 *	0.46 ns
S × Q	0.14 ns	1.4 ns	4.2 *	1.1 ns	0.05 ns	0.82 ns
Year (Y)	79.9 ***	2.6 ns	1.7 ns	5.9 *	0.38 ns	7.3 *
Y × S	3.2 ns	0.08 ns	2.0 ns	3.4 ns	1.2 ns	11.3 ***
Y × Q	7.2 *	0.34 ns	0.97 ns	1.5 ns	<0.01 ns	0.04 ns
Y × S × Q	3.2 ns	0.03 ns	0.79 ns	1.5 ns	0.07 ns	0.54 ns

ET_a from Equation (1); LF = D / I; S_{out}, salt exported by drainage; ΔSS, measured storage change in 0–100 cm; R, retained share of applied salt; ECe_{rz}, seasonal mean of the in-film 0–60 cm layer. Salt applied is in Table 1. Different letters within a column and season block indicate significant differences (Tukey HSD, $p < 0.05$); tests for ECe_{rz} used the natural-log scale, those for ΔSS and R untransformed data. F values: S, salinity; Q, quota; Y, year. Within-season terms and the S, Q and S × Q terms of the combined analysis were tested against the block × treatment error (15 df), and year terms against the residual error (18 df); *, ** and *** denote $p < 0.05$, 0.01 and 0.001; ns, not significant.

2.3. Water Balance and Soil Salinity

An on-site automatic station recorded air temperature, relative humidity, wind speed at 2 m, solar radiation and precipitation, and daily ET_0 was calculated with the FAO-56

Penman–Monteith equation [26] (Figure 1). Soil water storage in 0–100 cm was measured with a capacitance profile probe (one in-film access tube per plot) calibrated against gravimetric samples, before and after each irrigation and at least weekly. Drainage below 100 cm (D) was estimated with Darcy's law from matric potential at 90 and 110 cm (tensiometers) and the unsaturated hydraulic conductivity of undisturbed cores. Runoff was zero under film-mulched drip irrigation, and actual evapotranspiration (ET_a) was the residual of the water balance (Equation (1)). Water-balance estimates of ET_a are sensitive to errors in the drainage and storage terms [29]; as a check, seasonal ET_a at full quota (Section 3.1) can be compared with the 526 mm measured by eddy covariance over mulched drip-irrigated cotton in an arid oasis of northwest China [27].

Soil was augered in 20 cm increments to 100 cm at two positions in each plot: in-film (10 cm from the drip tape, within the narrow row) and inter-film (the bare strip between films). At each position and depth, three cores from the plot were bulked into one composite sample before analysis, so that each plot contributed one value per position, layer and date. The plot was the experimental unit ($n = 4$ plots per treatment in every test), and subsamples were never treated as replicates; the same rule applied to plant counts, harvest samples and the single gas chamber per plot. Full profiles were taken before sowing and at harvest, and the in-film 0–60 cm layer was additionally sampled on 10 June, 10 July and 10 August. ECe was measured in saturated paste extracts (vacuum extraction, 25 °C). Seasonal root-zone salinity (ECe_{rz}) is the time-weighted mean of the five dates of the in-film 0–60 cm layer mean.

2.4. Yield, Water Productivity and N_2O

Plant density and bolls per plant were counted on 20 consecutive plants in each of two rows, mean boll weight was determined from 50 mature bolls, and lint percentage from ginned subsamples. Seed cotton yield was the weight of a 24.6 m^2 harvest area (two films × 6 m) per plot. N_2O fluxes were measured with static opaque chambers (0.4 m × 0.4 m base, 0.4 m high) placed over the planted row, including one film hole, in all 24 plots on 20 dates per season, including days 1 and 4 after each fertigation, between 09:00 and 11:00 local time. Gas samples were taken at 0, 10, 20 and 30 min, analyzed by gas chromatography with electron-capture detection, and fluxes were calculated from the linear change in concentration [30]. Cumulative emission was obtained by trapezoidal integration between sampling dates. N_2O-N was converted to CO_2-equivalents with a 100-year global warming potential of 273 [31]; the system boundary is direct field N_2O only. Yield-scaled N_2O is cumulative N_2O-N per Mg of seed cotton. Because the design had no unfertilized control, no emission factor is reported.

2.5. Calculations

Actual evapotranspiration, with I irrigation, P precipitation, D drainage and ΔS the change in 0–100 cm water storage (all in mm), and the leaching fraction:

$$ET_a = I + P - D - \Delta S \quad (1)$$

$$LF = D / I \quad (2)$$

Salt applied (S_{in}), salt exported by drainage (S_{out}) and salt storage (SS) are in t ha^{-1}. $S_{in} = 0.01 \times I \times 0.64 \times EC_w$; $S_{out} = 0.01 \times D \times 0.64 \times 2 \times ECe_{80–100}$, the solution at field capacity being about twice as concentrated as the saturation extract ($ECe_{80–100}$ is the mean of the pre-sowing and harvest values of the in-film 80–100 cm layer in each season, and $2 \times ECe_{80–100}$ is reported as EC_{dr} in Table 1); ρ_i and h_i are bulk density (g cm^{-3}) and thickness (cm) of layer i, and 0.256 g kg^{-1} per dS m^{-1} converts ECe to salt content (saturation percentage

of 40%, dissolved solids of 0.64 g L^{-1} per dS m^{-1}). Layers were weighted 0.90 in-film and 0.10 inter-film by area:

$$SS = 0.1 \Sigma \rho_i h_i \times 0.256 (0.90 ECe_{in,i} + 0.10 ECe_{inter,i}) \quad (3)$$

The retained share of applied salt is $R = (S_{in} - S_{out}) / S_{in}$. R depends on the drainage estimate and is therefore not independent of LF. Measured storage change (ΔSS) is harvest minus pre-sowing SS, and its agreement with $S_{in} - S_{out}$ was used as a closure check. Water productivity (WP) and irrigation water productivity (IWP), with seed cotton yield Y in kg ha^{-1} and WP and IWP in kg m^{-3}, are:

$$WP = Y / (10 ET_a), \quad IWP = Y / (10 I) \quad (4)$$

Relative yield (RY) is Y divided by the mean of S1 plots with the same quota and year.

2.6. Statistical Analysis

Each season was first analyzed as a two-factor randomized complete block design, in which salinity, quota and the salinity × quota interaction were tested against the block × treatment error (15 df). Treatment effects over both seasons were then analyzed as a split-plot-in-time design. Salinity, quota and their interaction were whole-plot factors in randomized blocks and were tested against the block × treatment error (15 df). Year (the same plots in 2024 and 2025) was the subplot factor, and year terms (year, year × salinity, year × quota and year × salinity × quota) were tested against the residual error (18 df). Block was random and year fixed, because the two seasons are the only weather conditions of interest. Tables 2 and 3 give means ± standard error ($n = 4$ plots) for each season with the F values of the within-season analyses, followed by the two-season means with the F values of the combined analysis. The two-season means are retained because year × treatment interactions were not significant for nine of the twelve variables in these tables, so the pooled means estimate the treatment effects with the replication of both seasons; where year × treatment terms were significant or close to significance (ET_a, ECe_{rz}, ΔSS, bolls per plant, boll weight and yield), the seasonal means are interpreted in the text. Multiple comparisons used Tukey's honestly significant difference ($\alpha = 0.05$) on the error term of the respective analysis. Differences from S1W100 are given as percentages with 95% confidence intervals from the same error term. Soil layers and sampling positions were summarized per plot before analysis. ECe_{rz} and the inter-film ECe were analyzed on the natural-log scale because they are concentrations. Residuals were approximately normal (Shapiro–Wilk, $p > 0.05$) except for ΔSS ($p = 0.007$) and R ($p = 0.004$), for which the main conclusions were confirmed with rank-transformed analysis of variance; variances were homogeneous (Levene's test, $p > 0.05$) except for IWP ($p = 0.034$).

To test whether ECe_{rz} carries the effect of water salinity (H2), ln(yield) was regressed on year, quota, water electrical conductivity and ECe_{rz} using ordinary least squares with standard errors clustered by plot (24 clusters, t distribution with 23 df), which respects the two seasons per plot. The relation of ΔSS to salt applied was estimated for each quota by ordinary least squares with plot-clustered errors, and the difference between slopes was tested with a quota × salt interaction. Quota-specific log-linear slopes of ln(RY) on ECe_{rz} (centered at 3 dS m^{-1}) were estimated in the same way, and a threshold–slope function [5] was fitted by grid search (2.5–8.0 dS m^{-1}) with a cluster bootstrap (1000 resamples of plots) as an exploratory check. The same clustered regression related ln(N_2O) to ECe_{rz} and quota (H3). Analyses used custom scripts in Python 3.12 (NumPy, SciPy); no structural equation model was fitted, because 24 plots cannot support one.

Table 3. Yield components, seed cotton yield and water productivity in each season and over both seasons (mean ± SE, $n = 4$ plots, with F values from two-way and split-plot analysis of variance).

Treatment	Plants (10^4 ha^{-1})	Bolls Per Plant	Boll Weight (g)	Seed Cotton (kg ha^{-1})	WP (kg m^{-3})	IWP (kg m^{-3})
2024 season						
S1W100	23.21 ± 0.38 ab	5.23 ± 0.07 a	5.63 ± 0.09 a	6808 ± 129 a	1.25 ± 0.02 a	1.48 ± 0.03 b
S1W75	23.63 ± 0.21 a	4.93 ± 0.06 ab	5.31 ± 0.07 a	6109 ± 93 ab	1.25 ± 0.03 a	1.77 ± 0.03 a
S4W100	22.46 ± 0.30 b	5.05 ± 0.20 ab	5.52 ± 0.18 a	6462 ± 257 ab	1.19 ± 0.04 a	1.40 ± 0.06 b
S4W75	22.82 ± 0.17 ab	4.65 ± 0.06 b	5.24 ± 0.06 a	5552 ± 285 b	1.15 ± 0.08 a	1.61 ± 0.08 ab
S7W100	23.18 ± 0.19 ab	5.18 ± 0.09 a	5.49 ± 0.10 a	6508 ± 238 ab	1.21 ± 0.04 a	1.41 ± 0.05 b
S7W75	22.57 ± 0.29 b	4.59 ± 0.16 b	5.24 ± 0.08 a	5468 ± 319 b	1.11 ± 0.05 a	1.58 ± 0.09 ab
F values, two-way ANOVA, 2024						
Salinity (S)	6.1 *	2.8 ns	0.83 ns	2.5 ns	2.0 ns	2.5 ns
Quota (Q)	0.09 ns	25.5 ***	15.6 **	20.4 ***	1.5 ns	18.7 ***
S × Q	3.2 ns	1.00 ns	0.08 ns	0.26 ns	0.56 ns	0.49 ns
2025 season						
S1W100	23.27 ± 0.33 a	5.31 ± 0.07 a	5.67 ± 0.08 a	6970 ± 181 a	1.22 ± 0.03 a	1.39 ± 0.04 ab
S1W75	23.61 ± 0.21 a	4.89 ± 0.08 b	5.29 ± 0.09 b	6047 ± 115 a	1.18 ± 0.03 ab	1.61 ± 0.03 a
S4W100	22.62 ± 0.20 a	5.25 ± 0.09 ab	5.64 ± 0.09 a	6908 ± 264 a	1.22 ± 0.05 a	1.38 ± 0.05 b
S4W75	23.02 ± 0.36 a	4.89 ± 0.08 b	5.38 ± 0.08 ab	6058 ± 302 a	1.20 ± 0.07 ab	1.62 ± 0.08 a
S7W100	23.04 ± 0.23 a	5.00 ± 0.04 ab	5.39 ± 0.08 ab	6134 ± 259 a	1.09 ± 0.04 ab	1.23 ± 0.05 b
S7W75	22.35 ± 0.43 a	4.33 ± 0.13 c	5.08 ± 0.06 b	4946 ± 72 b	1.01 ± 0.01 b	1.32 ± 0.02 b
F values, two-way ANOVA, 2025						
Salinity (S)	3.6 ns	16.0 ***	9.6 **	13.1 ***	9.1 **	14.4 ***
Quota (Q)	<0.01 ns	47.4 ***	31.7 ***	31.4 ***	1.7 ns	20.5 ***
S × Q	2.1 ns	1.8 ns	0.38 ns	0.34 ns	0.26 ns	1.3 ns
Mean of 2024 and 2025						
S1W100	23.24 ± 0.35 ab	5.27 ± 0.06 a	5.65 ± 0.08 a	6889 ± 93 a	1.24 ± 0.02 a	1.44 ± 0.02 b
S1W75	23.62 ± 0.16 a	4.91 ± 0.07 bc	5.30 ± 0.07 cd	6078 ± 64 b	1.22 ± 0.01 a	1.69 ± 0.02 a
S4W100	22.54 ± 0.23 b	5.15 ± 0.11 ab	5.58 ± 0.10 ab	6685 ± 202 a	1.21 ± 0.03 a	1.39 ± 0.04 b
S4W75	22.92 ± 0.17 ab	4.77 ± 0.05 cd	5.31 ± 0.06 bcd	5805 ± 104 bc	1.18 ± 0.03 a	1.61 ± 0.03 a
S7W100	23.11 ± 0.15 ab	5.09 ± 0.06 abc	5.44 ± 0.09 abc	6321 ± 145 ab	1.15 ± 0.02 ab	1.32 ± 0.03 b
S7W75	22.46 ± 0.31 b	4.46 ± 0.13 d	5.16 ± 0.07 d	5207 ± 174 c	1.06 ± 0.03 b	1.45 ± 0.05 b
F values, split-plot ANOVA over both seasons						
Salinity (S)	7.3 **	9.1 **	4.9 *	15.8 ***	13.7 ***	17.6 ***
Quota (Q)	0.05 ns	56.9 ***	37.6 ***	77.4 ***	5.7 *	66.8 ***
S × Q	4.3 *	2.1 ns	0.26 ns	0.74 ns	1.3 ns	2.2 ns
Year (Y)	<0.01 ns	0.02 ns	0.01 ns	0.05 ns	1.9 ns	10.6 **
Y × S	0.65 ns	6.5 **	3.4 ns	3.5 ns	2.1 ns	3.0 ns
Y × Q	0.02 ns	0.28 ns	0.17 ns	0.13 ns	<0.01 ns	0.30 ns
Y × S × Q	0.02 ns	0.23 ns	0.11 ns	0.09 ns	0.12 ns	0.23 ns

WP = Y / (10 ET_a) and IWP = Y / (10 I) (Equation (4)). Letters and F values as in Table 2. *, ** and *** indicate significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively; ns, not significant ($p \geq 0.05$).

3. Results

3.1. The Quota, Not Water Salinity, Set Evapotranspiration and Drainage

Reducing the quota to 75% lowered ET_a by 10–11% at every salinity (489–500 versus 549–557 mm; quota, F = 489, $p < 0.001$; Table 2). At full quota, ET_a was 549–557 mm across salinities, with no pairwise difference (salinity, $p = 0.042$). LF was higher at full quota (5.5–10.9%) than under W75 (2.7–4.6%; quota, F = 15.2, $p = 0.001$) and tended to rise with salinity ($p = 0.050$). ET_a averaged 514 mm in 2024 and 534 mm in 2025 ($p < 0.001$), the year with higher ET_0 and lower precipitation. Within each season, quota lowered ET_a (2024: F = 196; 2025: F = 575; both $p < 0.001$), whereas salinity lowered it only in 2025 (F = 11.5, $p < 0.001$), mainly at S7W75 (488 mm against 505–511 mm in the other W75 treatments; Table 2). The salinity × quota interaction for ET_a was not significant in either season ($p = 0.43$ and 0.09) or over both seasons ($p = 0.87$). LF was lower under W75 in both

seasons ($p = 0.003$ and 0.009) and did not differ between years ($p = 0.12$), and drainage below 100 cm amounted to 9–55 mm per season (Table 1).

3.2. Applied Salt Stayed in the Profile, and More of It Stayed Under the 75% Quota

Salt applied with the water rose from 2.0–2.8 t ha^{-1} per season at S1 to 20–23 t ha^{-1} at S7 under full quota (Table 1), and measured storage change followed it: ΔSS was 2.0 t ha^{-1} at S1W100, 9.9 at S4W100 and 18.0 at S7W100 (salinity, F = 639, $p < 0.001$; Table 2). Per ton of salt applied, ΔSS increased by 0.84 t at full quota (95% CI 0.76–0.92) and by 1.05 t at W75 (0.96–1.14), a difference of 0.21 t (95% CI 0.09–0.32; $p < 0.001$; Figure 2a); the W75 interval includes complete retention. Fitted to the treatment means of each season, the slope was again larger under W75 in 2024 (1.09 versus 0.91) and in 2025 (1.00 versus 0.81), and ΔSS was larger in 2025 than in 2024 in every treatment except S4W100 (year, $p = 0.026$; year × salinity, $p = 0.058$; Table 2). ΔSS calculated from the balance ($S_{in} - S_{out}$) agreed with the measured values (r = 0.97, slope 1.04; mean absolute difference 1.2 t ha^{-1}, or 13% of the mean calculated change; Figure 2b). Drainage exported 0.5–4.4 t ha^{-1} per season, so the calculated retained share R was 0.59 at S1W100, 0.82 at S4W100 and 0.79 at S7W100, and higher at every salinity under W75 (0.75, 0.94 and 0.93; quota, F = 7.2, $p = 0.017$; salinity × quota, $p = 0.95$). A rank-transformed analysis gave the same conclusion (quota, $p = 0.004$). Because W75 applied 25% less salt, ΔSS under W75 was only 1.1 and 1.7 t ha^{-1} lower at S4 and S7 (quota, $p = 0.009$; rank-based $p = 0.024$). The salinity × quota interaction was not significant for ΔSS ($p = 0.34$), R ($p = 0.95$) or LF ($p = 0.27$), but it was for S_{out} ($p = 0.035$), because drainage exported disproportionately more salt at S7W100 than in the other combinations.

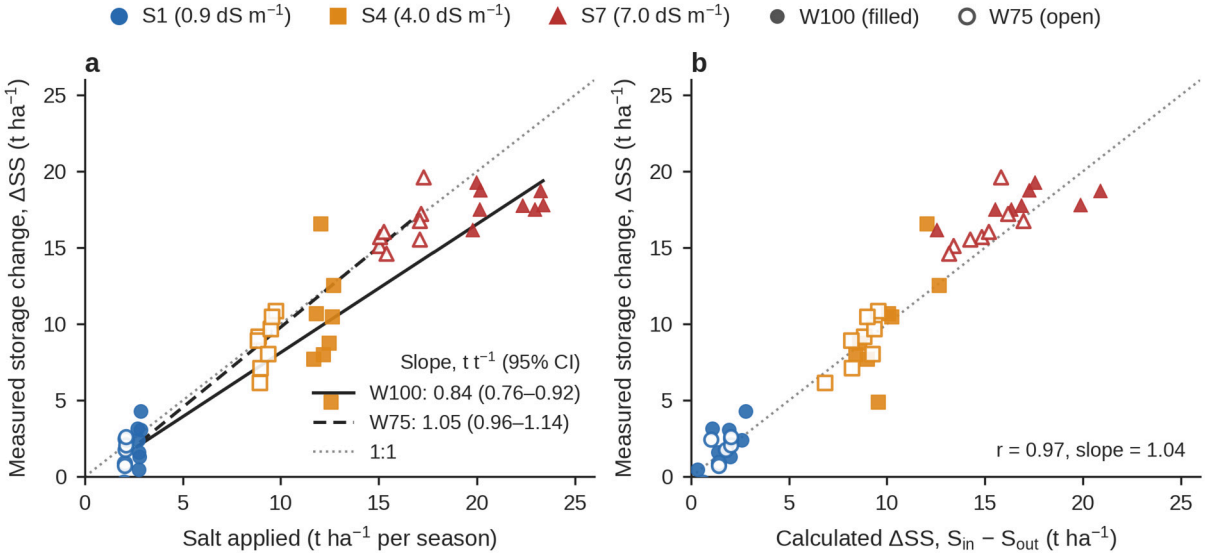


Figure 2. Salt retention in the 0–100 cm profile. (**a**) Measured storage change (ΔSS) against salt applied for each plot-season ($n = 48$); lines are least-squares fits for each quota (solid, W100; dashed, W75) and the dotted line marks full retention (1:1). (**b**) Measured ΔSS against ΔSS calculated from the salt balance ($S_{in} - S_{out}$); the dotted line is 1:1. Color denotes water salinity (S1, S4, S7) and symbols denote the quota (filled, W100; open, W75).

Seasonal ECe_{rz} was 3.23 dS m^{-1} at S1W100, 4.54 at S4W100 (+40.5%, 95% CI +28.1 to +53.0) and 5.39 at S7W100 (+66.9%, +54.5 to +79.3), with no detectable effect of quota (quota, $p = 0.51$; salinity × quota, $p = 0.46$); analyzed season by season, salinity raised ECe_{rz} in both years (2024: F = 28.2; 2025: F = 83.4; both $p < 0.001$), and neither quota ($p \geq 0.54$) nor the interaction ($p \geq 0.29$) was significant. The seasonal trajectories differed between

years (year × salinity, F = 11.3, $p < 0.001$; Figure 3). At S7W100, ECe_{rz} rose from 3.1 dS m^{-1} before sowing in 2024 to 6.5 at harvest, started 2025 at 4.9 after the winter irrigation, and reached 8.4 at the 2025 harvest. At S1W100 it stayed between 2.7 and 3.6 dS m^{-1}. The winter irrigation removed 3.0, 9.1 and 11.1 t ha^{-1} at S1W100, S4W100 and S7W100 (20%, 37% and 36% of harvest storage). Pre-sowing storage in 2025 was 11.0–11.6 t ha^{-1} in S1 plots, 14.3–15.3 in S4 and 17.4–19.5 in S7, against 13.2 at the start of the experiment.

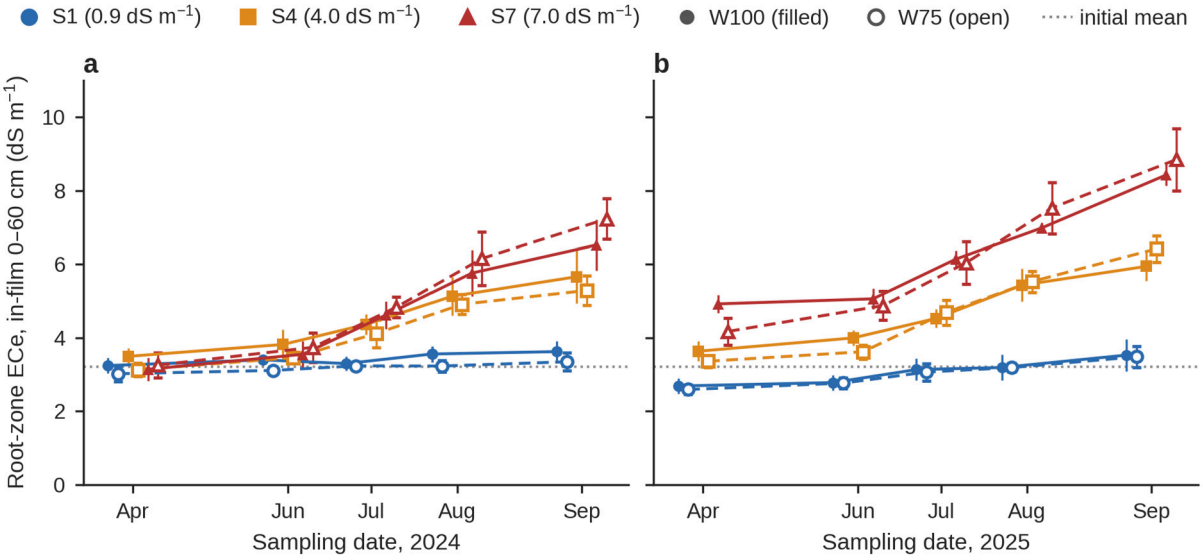


Figure 3. Seasonal root-zone salinity (ECe, in-film 0–60 cm layer, saturation extract) of the six treatments in (**a**) 2024 and (**b**) 2025. Points are means of four plots (offset horizontally within each date for clarity) and bars are standard errors; the dotted line is the initial mean. Color denotes water salinity and line type and symbols denote the quota (solid and filled, W100; dashed and open, W75). A uniform 200 mm fresh-water irrigation was applied between the seasons.

At the 2024 harvest the in-film profile at S4 and S7 already peaked at 40–80 cm (6.7–8.3 dS m^{-1} at S4W100 and 7.6–10.2 dS m^{-1} at S7W100), whereas S1 plots stayed between 2.8 and 3.8 dS m^{-1}, and the inter-film surface held 10.7, 15.8 and 24.8 dS m^{-1} at S1W100, S4W100 and S7W100 (Figure 4a,b). At the 2025 harvest the in-film ECe profile peaked at 40–80 cm in every treatment (3.9 dS m^{-1} at S1W100, 7.0 at S4W100 and 11.2 at S7W100), whereas the surface 0–20 cm of the inter-film strip held 9.7, 17.0 and 24.3 dS m^{-1} at S1W100, S4W100 and S7W100 and declined to 3.0, 6.0 and 9.3 dS m^{-1} at 80–100 cm (Figure 4c,d). Between the two harvests, ECe of the 60–80 and 80–100 cm in-film layers at S7W100 rose from 10.2 and 7.1 to 11.2 and 10.6 dS m^{-1}, so the second season moved salt deeper into the profile. Inter-film surface ECe, analyzed on the log scale for both seasons, increased with water salinity (F = 144.9, $p < 0.001$) and did not differ between quotas ($p = 0.25$).

3.3. Yield Declined with Salinity and Followed Root-Zone ECe

Seed cotton yield was 6889 kg ha^{-1} at S1W100 and 6685 at S4W100 (−3.0%; 95% CI −8.7 to +2.7), and fell to 6321 at S7W100 (−8.2%; −13.9 to −2.5). Under W75 it was 6078 (−11.8%), 5805 (−15.7%) and 5207 kg ha^{-1} (−24.4%; −30.1 to −18.7) at S1, S4 and S7 (Table 3). Both factors were significant (salinity, F = 15.8, $p < 0.001$; quota, F = 77.4, $p < 0.001$) and the interaction was not ($p = 0.49$). Relative to S1 with the same quota, the S7 penalty was 8.2% at full quota and 14.3% at W75. The salinity penalty tended to grow in the second season (year × salinity, $p = 0.054$): S7W100 yield was −4.4% relative to S1W100 in 2024 and −12.0% in 2025, and S7W75 was −10.5% and −18.2% relative to S1W75. Analyzed

season by season, quota reduced yield in both years (2024: F = 20.4; 2025: F = 31.4; both $p < 0.001$), salinity was significant only in 2025 (F = 13.1, $p < 0.001$; 2024: $p = 0.12$), and the salinity × quota interaction was not significant in either season ($p = 0.78$ and 0.72; Table 3); over both seasons it was significant only for plant density ($p = 0.034$), where treatment means differed by less than 1.2×10^4 plants ha^{-1}. At 4.0 dS m^{-1} the penalty did not grow: S4W100 yielded 5.1% less than S1W100 in 2024 and 0.9% less in 2025, and S4W75 was 9.1% below S1W75 in 2024 and 0.2% above it in 2025. Bolls per plant carried most of the year × salinity pattern (year × salinity, $p = 0.008$): at S7W75 they fell from 4.59 in 2024 to 4.33 in 2025, whereas both S4 treatments set more bolls in 2025. Bolls per plant (5.27 to 4.46), boll weight (5.65 to 5.16 g) and plant density (23.2 to 22.5 × 10^4 ha^{-1}) all declined from S1W100 to S7W75, and lint percentage changed by less than one point (41.7 to 41.2%; salinity, $p = 0.011$). Yield averaged 6151 kg ha^{-1} in 2024 and 6177 in 2025 ($p = 0.82$). Yield calculated from components agreed with harvested yield within 2.8% for every treatment mean (plot-level mean absolute difference 5.3%, maximum 17%).

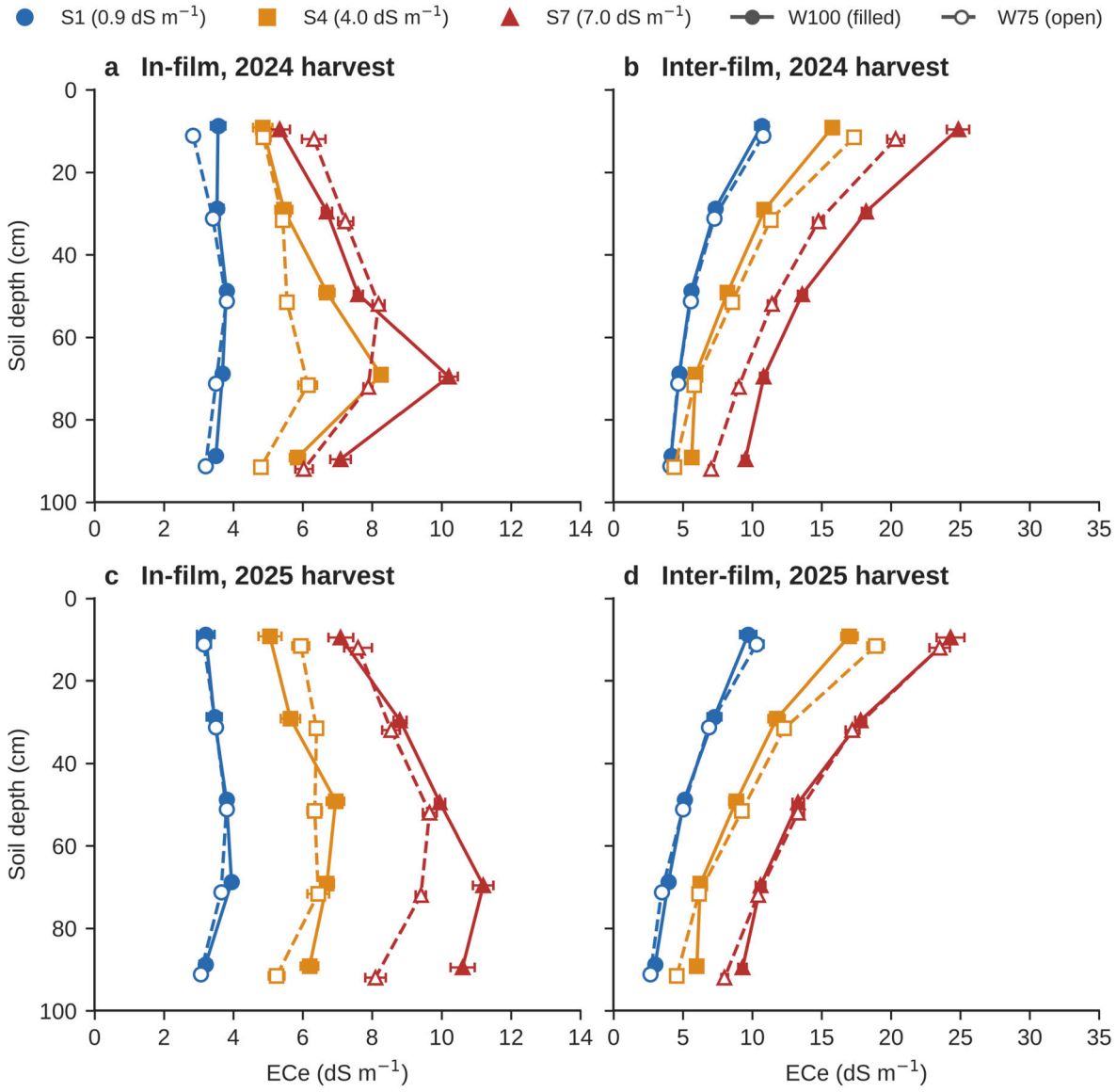


Figure 4. Profiles of ECe at the 2024 (**a**,**b**) and 2025 (**c**,**d**) harvests in the in-film zone (**a**,**c**) and the inter-film strip (**b**,**d**), by 20 cm layer. Points are means of four plots (offset vertically for clarity) and bars are standard errors. Symbols and line types as in Figure 3.

Water salinity alone predicted ln(yield) with a coefficient of −0.0204 per dS m^{-1} ($p < 0.001$; $R^2 = 0.68$ with year and quota in the model), and ECe_{rz} alone with −0.0481 per dS m^{-1} ($p < 0.001$; $R^2 = 0.71$). With both in the model, the water-salinity coefficient fell to −0.0068 ($p = 0.30$), a 66% reduction, and the ECe_{rz} coefficient to −0.0355 ($p = 0.057$); the two variables were strongly correlated (r = 0.82). Relative yield declined with ECe_{rz} by 3.3% per dS m^{-1} at full quota (95% CI −5.7 to −0.8; $p = 0.014$) and by 5.8% at W75 (−8.3 to −3.2; $p < 0.001$) (Figure 5a). The difference between the two slopes was not significant ($p = 0.13$). A threshold–slope function could not be identified with 24 plots: the full-quota threshold was 5.05 dS m^{-1} (bootstrap 95% CI 2.50–5.05, reaching the lower limit of the search range) and the W75 threshold 3.40 dS m^{-1} (2.50–4.10).

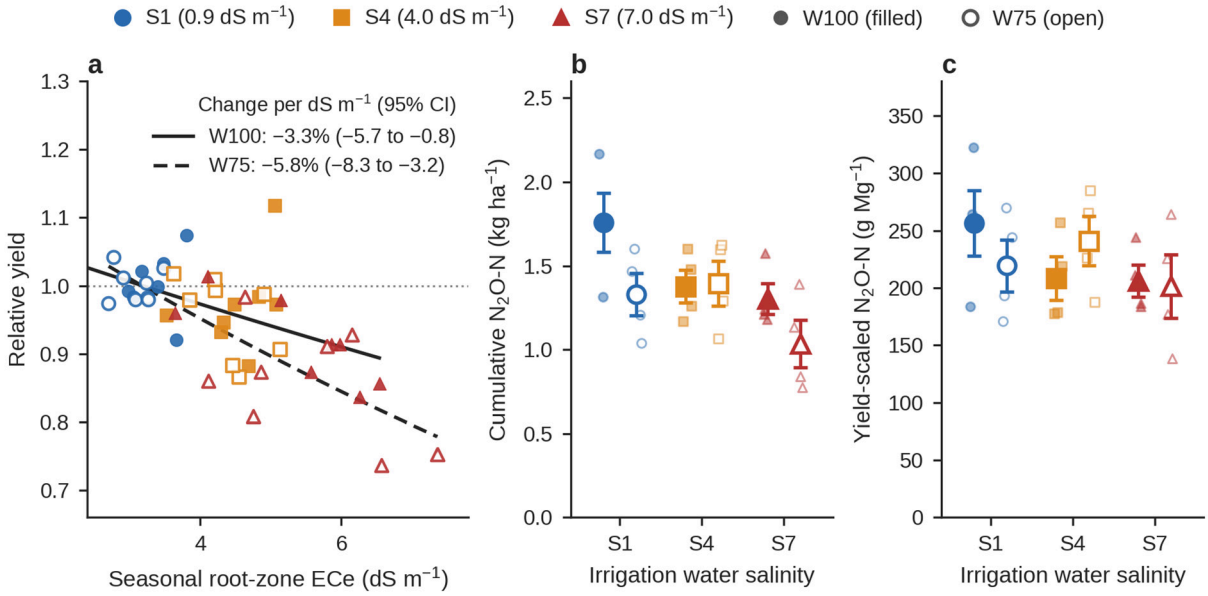


Figure 5. Yield and N_2O responses. (**a**) Relative yield against seasonal root-zone ECe for all plot-years ($n = 48$); relative yield is yield divided by the mean S1 yield with the same quota and year, and lines are log-linear fits for each quota. (**b**) Cumulative N_2O-N and (**c**) yield-scaled N_2O-N; small symbols are plot means over the two seasons and large symbols are treatment means ± standard error ($n = 4$ plots, offset horizontally by quota). Color denotes water salinity and symbols the quota as in Figure 2.

Water productivity fell with salinity ($F = 13.7$, $p < 0.001$) and slightly with the quota ($p = 0.030$): WP was 1.24 kg m^{-3} at S1W100, 1.15 at S7W100 and 1.06 at S7W75 (−13.8%; −19.5 to −8.2). Irrigation water productivity was higher under W75 at every salinity (+18%, +16% and +10% at S1, S4 and S7; quota, $F = 66.8$, $p < 0.001$). In the seasonal analyses, salinity lowered WP in 2025 ($F = 9.1$, $p = 0.003$), when S7W75 had the lowest value (1.01 kg m^{-3}), but not in 2024 ($p = 0.16$), and no salinity × quota interaction was detected for WP or IWP in either season ($p \geq 0.31$).

3.4. N_2O Emissions Fell with Salinity and Quota, but Yield-Scaled Emissions Did Not Differ

Cumulative N_2O-N was 1.76 ± 0.18 kg ha^{-1} at S1W100, 1.33 ± 0.13 at S1W75, 1.38 ± 0.10 at S4W100, 1.40 ± 0.13 at S4W75, 1.30 ± 0.09 at S7W100 and 1.04 ± 0.14 at S7W75 (Figure 5b), equal to 446–755 kg CO_2-eq ha^{-1} and to 0.43–0.73% of the N applied (gross ratio). Both factors lowered emissions (salinity, $F = 6.1$, $p = 0.012$; quota, $F = 6.6$, $p = 0.022$) without an interaction ($p = 0.14$) or a year effect ($p = 0.60$). Relative to S1W100, cumulative N_2O was 22% lower at S4W100, 26% at S7W100, 24% at S1W75, 21% at S4W75 and 41% at S7W75 (95% CI −60 to −23); only S7W75 differed from S1W100 in pairwise

tests. In the 2025 season, fluxes averaged 104 µg N m^{-2} h^{-1} one day after fertigation, 33 four days after, and 4.5 outside the fertigation period. With year and quota in the model, ln(N_2O) decreased by 9.6% per dS m^{-1} of ECe_{rz} ($p < 0.001$) and the 75% quota lowered emissions by 16.7% ($p = 0.020$; $R^2 = 0.31$).

Yield-scaled N_2O-N ranged from 201 to 257 g Mg^{-1} seed cotton (Figure 5c): 257 ± 29 at S1W100 and 201 ± 28 at S7W75 (−21%; 95% CI −43 to +0). This is about half the relative reduction in area-scaled emission, because yield fell by 24% over the same comparison. The differences in yield-scaled N_2O among treatments were not significant (salinity, $p = 0.21$; quota, $p = 0.84$; interaction, $p = 0.20$).

4. Discussion

4.1. Salt Retention, Not Water Salinity Alone, Defines What the Root Zone Experiences

The main result of this study is that most of the salt delivered by brackish water stayed in the profile, and more of it stayed under the 75% quota. Measured storage change rose by 0.84 t per ton of salt applied at full quota and by 1.05 t at W75 (difference 0.21 t, 95% CI 0.09–0.32), and the W75 interval includes complete retention, which supports H1. Retained storage rose from 2.0 to 18.0 t ha^{-1} per season at full quota, with ΔSS tracking salt applied closely (r = 0.94 at W100 and 0.98 at W75). The calculated retained share R followed the same order (0.75–0.94 under W75 versus 0.59–0.82 at full quota), but R and LF both derive from the drainage estimate, so their covariation is structural and was not used as evidence; the soil measurements are the independent test. That a smaller LF is the pathway is therefore an inference from the balance, in which drainage exported 0.5–4.4 t ha^{-1} per season, mostly at full quota (Table 2), and it parallels the finding of Aragüés et al. [19] that the rise in root-zone salinity under deficit-irrigated orchards varies inversely with the leaching fraction. Salt load dominated absolute accumulation, and quota left ECe_{rz} unchanged ($p = 0.51$) because the 25% reduction in salt applied was offset by the near absence of drainage under W75. In our interpretation, the pattern follows the physics of a drip system: salt applied with the water is conserved (balance closure, r = 0.97), is carried to the wetting front and the margins of the wetted volume, and leaves only with drainage, which is small when the quota is limited. Drainage estimated from Darcy fluxes is the least certain term; an error in D would shift R and LF without changing the measured ΔSS.

Our retention values can be compared with those of other salt-balance studies under drip irrigation. In northern Xinjiang, HYDRUS-2D simulations of typical irrigation schedules under film mulch produced net desalination of the root zone [16], and scenarios with saline water (3.1 and 7.4 dS m^{-1}) and low antecedent salinity produced accumulation of about 4–14 t ha^{-1} over a season [32]. Our measured gains at S4 and S7 (8.8–18.0 t ha^{-1} per season; Table 2) lie within and somewhat above that simulated range, which is plausible because LF here was only 2.7–10.9% and the profile was not leached during the season. The fresh-water treatments behaved differently from the simulated desalination: they gained 1.6–2.0 t ha^{-1} per season but lost more than this during the winter irrigation, so that their pre-sowing storage in 2025 was below the initial value. Long-term monitoring under mulched drip irrigation has likewise found salt accumulating in the subsoil and in the bare soil between mulches when no leaching is applied [33], the same two sinks that held the salt in this study (Figure 4), and fresh-water leaching at selected growth stages has been shown to remove part of the salt delivered by brackish water [15], as the winter irrigation did here.

Carry-over between seasons made the first season an unreliable guide. S7W100 yield was −4.4% relative to S1W100 in 2024 and −12.0% in 2025, and ECe_{rz} at S7W100 started 2025 at 4.9 dS m^{-1} against 3.1 a year earlier. The uniform 200 mm winter irrigation removed 20–37% of the salt stored at harvest. That was enough to keep fresh-water plots below

their initial storage (11.0–11.6 versus 13.2 t ha^{-1}) but not S7 plots, which began 2025 with 17.4–19.5 t ha^{-1}. At 4.0 dS m^{-1}, carry-over was not reflected in yield over two seasons: S4W100 yielded 5.1% less than S1W100 in 2024 and 0.9% less in 2025, although its seasonal ECe_{rz} rose from 4.43 to 4.65 dS m^{-1}. Corwin et al. [20] showed that steady-state leaching requirements misjudge transient conditions such as this accumulate-and-flush behavior, and our fresh-water result agrees with the finding of Luo et al. [17] that long-term water-saving practices can sustain soil condition and yield on reclaimed saline-alkali land. Wang et al. [34] identified, by meta-analysis, the factors controlling water and salt distribution under mulched drip systems; the retained share and LF reported here are candidate quantities for such syntheses. Two seasons say nothing about the equilibrium that repeated cycles would reach.

The distribution of salt was strongly non-uniform. The inter-film surface reached 24.3 dS m^{-1} at S7W100, whereas in-film ECe peaked at 40–80 cm, the redistribution described by Chen et al. [9] and Zhang et al. [15] beneath drip emitters; Lin et al. [35] documented non-uniform salt distribution within drip subunits under arid conditions. Because ECe_{rz} was sampled only in the in-film 0–60 cm layer, it may understate the salinity experienced by roots that explore the wetted margin, and it cannot show whether salt precipitated as gypsum or carbonate, which would lower ECe without leaching. Process models of water, heat and salt transport under film-mulched drip irrigation [36,37] are the natural route to test these possibilities.

Retention has been under-reported for two reasons. Experiments are usually organized around treatment means of salinity and yield, and salt mass balances are rarely closed because drainage below the root zone is hard to measure. Most are also confined to a single season, in which carry-over cannot be seen. Reporting S_{in}, S_{out}, R and LF alongside ECe, as done here, adds little cost and makes brackish-water use comparable across quotas and sites, which a water-quality class alone does not.

4.2. Root-Zone ECe Tracks Yield Loss, but the Data Cannot Separate It from Water Salinity or Fix a Threshold

H2 is supported in part. In our data, ECe_{rz} and water salinity explained yield about equally well (R^2 = 0.71 and 0.68), but, once ECe_{rz} entered the model, the coefficient of water salinity fell by 66% and lost significance ($p = 0.30$). This is the pattern expected if water salinity acts on yield through root-zone salinity, the route by which salt reduces water uptake in the osmotic phase described by Munns and Tester [3]. ECe_{rz} itself was marginal ($p = 0.057$) and the two variables were strongly correlated (r = 0.82), so we conclude only that ECe_{rz} is the better-behaved state variable, not that it is the causal pathway. Soil water potential and ion composition co-vary with ECe_{rz} and were not separated in this study. Moreover, Wang et al. [10] showed by inverse modelling of drip-irrigated tomato that root water uptake follows the salinity of the wetted zone rather than that of a sampled layer, so our in-film layer mean is an index of the salinity that roots experience rather than a measure of it.

In this experiment, yield declined at seasonal ECe_{rz} values below the handbook threshold for cotton of 7.7 dS m^{-1} given by Maas and Hoffman [5] and Ayers and Westcot [6]: at S7W100, where ECe_{rz} averaged 5.4 dS m^{-1}, yield was 8.2% lower than at S1W100. Ren et al. [11] and Li et al. [12] likewise derived their own yield-compatible salinities and water–salt thresholds for cotton under mulched drip irrigation rather than adopting handbook values. We attribute this gap to the mean ECe of a sampled in-film layer differing from the uptake-weighted salinity that the handbook function assumes; this explanation was not tested here. The exploratory threshold–slope fits were unstable, and the full-quota threshold interval spanned the search range, so no threshold is proposed.

Quota modified the yield response in direction only. The log-linear slope was 3.3% per dS m^{-1} at full quota and 5.8% at W75, with overlapping intervals and a non-significant difference ($p = 0.13$), and the salinity × quota interaction for yield was also not significant ($p = 0.49$). The second clause of H2 is therefore not supported at the sample size of this study. The salinity penalty relative to S1 with the same quota was larger at W75 (14.3% versus 8.2% at S7), which differs from the report of Lin et al. [14] that salt stress effects were mitigated under water deficit in southern Xinjiang. Because ECe_{rz} was the same under both quotas here, equal root-zone salinity met a smaller water supply, whereas in a design in which deficit also lowers ECe_{rz} the two effects could partly offset each other; this was not tested. Bolls per plant fell most (−15% from S1W100 to S7W75, against −9% for boll weight and −3% for plant density), so boll retention was the component most associated with yield loss, but no physiological measurements were made and the data do not identify why.

Alternative explanations deserve mention. Plant density fell by 3.4% from S1W100 to S7W75, so part of the yield loss may reflect stand establishment, but the common fresh-water emergence irrigation and the small size of this effect make it a minor contributor to a 24.4% loss. Block and plot effects are absorbed by the design, with blocks random and the same plots tracked across years. Finally, the penalty could reflect ion-specific injury rather than osmotic stress, the two phases distinguished by Munns and Tester [3]; individual ions in the blended waters were not examined, and ECe cannot distinguish the two.

4.3. Water Productivity and N_2O: Reductions Came with a Smaller Crop

Water productivity changed little with quota and fell only at the highest salinity (−13.8% at S7W75). At S1 the 75% quota lowered ET_a by 10.4% and yield by 11.8%, a yield response factor of 1.1, higher than the 0.85 tabulated for cotton by Doorenbos and Kassam [38], although the uncertainty is large. Cheng et al. [39] quantified in a global meta-analysis the yield and water productivity responses of seed cotton to deficit irrigation; the S1 comparison here is a single-site case of that kind. The deficit saved 120 mm of irrigation and raised IWP by 18% at S1 and by 10% at S7, while the same saving cost 17.6% of yield at S7 against 11.8% at S1.

The lower emissions under W75 are consistent with the dependence of N_2O production on water-filled pore space shown by Linn and Doran [21] and reviewed by Butterbach-Bahl et al. [22]: a smaller quota keeps less of the wetted volume at the water contents where nitrification and denitrification release most N_2O. Three mechanisms reported in the literature can explain why cumulative N_2O declined as irrigation water salinity increased. First, salts lower the osmotic potential of the soil solution and suppress microbial biomass and activity [40]; in a drip-irrigated cotton field near Shihezi, irrigation water of 4.6 and 8.0 dS m^{-1} reduced the abundance of ammonia-oxidizing archaea and bacteria and the potential nitrification rate in fertilized plots, and lowered nitrate and nitrite reductase activities [41]. Slower nitrification of the fertigated urea and lower reductase activity both limit the substrate and the enzyme capacity for N_2O production. Second, saline irrigation in soils of the same region raised NH_4^+-N and ammonia volatilization while lowering NO_3^--N [42], so part of the applied N was probably lost as NH_3 before it could be nitrified, a loss favored by the soil pH of 8.1. Third, the smaller crop at S7 probably supplied less root-derived carbon for denitrification; this is our inference and was not measured. The direction of the salinity effect is not universal. In a single-season study at the same station, brackish and saline water increased N_2O emission from fertilized drip-irrigated cotton, which the authors attributed to incomplete nitrification, nitrite accumulation and inhibition of N_2O reductase [43], and the meta-analysis of Zhou et al. [23] showed that salinization alters soil nitrogen pools, cycles and fluxes. The net effect therefore appears to depend on

the salinity range, soil water content and carbon supply. Neither pathway was measured in our experiment, because pore space, nitrification, denitrification and microbial indicators were not recorded, so these are plausible explanations rather than findings. The data establish an association of $\ln(N_2O)$ with ECe_{rz} (−9.6% per dS m^{-1}) and a separate quota effect (−16.7%). For H3 the relevant comparison is between the area-scaled (−41%) and yield-scaled (−21%, 95% CI −43 to +0) reductions at S7W75. Differences in yield-scaled N_2O among treatments were not detectable, so the lower emission per hectare under saline or deficit irrigation is consistent with a smaller crop rather than a lower emission intensity. Absence of a detectable difference is not evidence of equivalence, given the width of the intervals. The gross ratio of 0.43–0.73% of N applied is not an emission factor, and the boundary, direct N_2O only, excludes methane, soil carbon change and the energy used for pumping and blending.

4.4. Management Implications and Limits

The framework, rather than the numbers, is what should transfer. Retained share, LF and ECe_{rz} can be obtained in any drip-irrigated system with a restricted wetted volume and limited drainage, and they allow brackish-water use to be compared across quotas and seasons; the slopes and yield penalties reported here are specific to this soil, cultivar and climate.

Four points follow, each bounded by two seasons at one site. First, 4.0 dS m^{-1} water at full quota cost 3.0% of yield (95% CI −8.7 to +2.7%), which is not distinguishable from zero, but seasonal ECe_{rz} at S4W100 was 4.5 dS m^{-1} and harvest values in 2025 reached 5.9 dS m^{-1}, so the margin depends on winter leaching. Second, combining 4.0 dS m^{-1} or stronger water with the 75% quota should be avoided: S4W75 yielded 15.7% less than fresh water at full quota, of which 4.5 points reflect salinity and the rest the deficit, and the salinity share rose to 14.3 points at S7. Third, the uniform winter irrigation removed 36% of end-of-season storage at S7W100 and still left plots 4–6 t ha^{-1} above the initial storage, so higher salinities need larger leaching depths or blending with fresh water [20,44]. Fourth, monitoring ECe_{rz} and adjusting quota or leaching accordingly fits the root-zone-based smart irrigation concept of Liu et al. [18] and the economic and ecological optimization of brackish water use proposed by Xu et al. [45]; Duan et al. [46] tested magnetoelectric treatment of brackish water for cotton in southern Xinjiang, and such treatment could be compared on the same salt-balance basis.

The limitations are specific. The experiment covers two seasons, one loam soil, one cultivar and a groundwater table below 4.5 m, so the results describe short-term responses and carry-over, not long-term salinization or sodification, and ionic composition and sodicity were not examined. Slopes rest on 24 plots, regressions on ECe_{rz} involve collinearity and few clusters, and ΔSS and R were analyzed on untransformed data with rank-based confirmation. ECe_{rz} was sampled in the in-film layer only; drainage water was not sampled, so its salinity in Table 1 is an estimate from the 80–100 cm saturation extract, and the irrigation schedule relied on a single on-site weather station. N_2O was measured with chambers over the planted row, without an unfertilized control or ancillary soil variables, and no economic analysis was performed. Agreement between yield components and harvested yield was looser at plot level (maximum difference 17%) than at treatment level.

5. Conclusions

In two seasons of mulched drip irrigation on the northern slope of the Tianshan Mountains, the salt delivered by brackish water stayed largely in the profile, and storage change per ton of salt applied was larger under a 75% quota than at full quota (1.05 versus 0.84 t t^{-1}). Yield declined with salinity (−3.0% at 4.0 dS m^{-1} and −8.2% at 7.0 dS m^{-1} at

full quota; −24.4% at 7.0 dS m^{-1} with the 75% quota) and followed seasonal root-zone ECe (−3.3% per dS m^{-1} at full quota and −5.8% at the 75% quota), with the effect of water salinity shrinking by 66% once ECe was accounted for. The penalty at 7.0 dS m^{-1} grew from the first to the second season (−4.4% to −12.0%). Cumulative N_2O fell by up to 41% with salinity and deficit irrigation, but yield-scaled N_2O did not differ detectably, so the reduction should not be read as an environmental benefit independent of a smaller crop.

These findings matter because water-quality classes cannot express the quota dependence or the seasonal carry-over of salt, whereas root-zone ECe and the leaching fraction can. They apply to mulched drip-irrigated cotton on a loam soil with deep groundwater over the two seasons studied, in which brackish water near 4 dS m^{-1} was compatible with full-quota irrigation followed by fresh-water winter irrigation and higher salinity combined with deficit irrigation was not. They do not address long-term salinization, sodification or soil carbon, and the thresholds and the N_2O mechanisms need multi-year, multi-site tests with measured ion composition, soil moisture and an unfertilized control.

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