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Drainage, salt-leaching impacts, and the growth of *Salicornia bigelovii* irrigated with different saline waters

Mansoor Al-Tamimi [a], Steve Green [b], Wasel Abou Dahr [a], Ahmed Al-Muaini [a], Dionysia Lyra [c], Khalil Ammar [c], Mohamed Dawoud [a], Paul Kenyon [d], Peter Kemp [d], Lesley Kennedy [e], Andrew McLachlan [b], Brent Clothier [b,*]

[a] *Environment Agency - Abu Dhabi, Abu Dhabi, United Arab Emirates*
[b] *The New Zealand Institute for Plant and Food Research Limited, Palmerston North, New Zealand*
[c] *International Centre for Biosaline Agriculture, Dubai, United Arab Emirates*
[d] *Massey University, Palmerston North, New Zealand*
[e] *OnlyFromNZ, Wellington, New Zealand*

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ABSTRACT

We sought to assess the impact on groundwater of using three types of saline waters to irrigate the halophyte *Salicornia bigelovii* Torrey in the hyper-arid United Arab Emirates. These were groundwater (GW) at 25 dS m^{-1}, reverse-osmosis brine (RO) from a desalination unit at 40 dS m^{-1}, and the aquabrine (AQ) effluent from land-based aquaculture in tanks filled with RO brine, also at 40 dS m^{-1}. The three waters were applied through bubblers (BUB), pressure-compensated drippers (PCD), or subsurface irrigation tape (SUB). The yields of *Salicornia* fresh tips, harvest forage, and seed were greatest for AQ applied through BUB, being 650 g m^{-2}. We found 2–2.6 kg m^{-2} for dry forage yield with AQ through BUB, compared with 1–2.3 kg m^{-2} for the other waters and emitter devices. The highest water productivities WP_I (kg m^{-3}) across all three crop-outputs came from Aquabrine applied by pressure-compensated drippers. We assessed the gross economic water productivity ($GEWP_I$, \$ m^{-3}) based solely on gross revenue. The $GEWP_I$ was highest for AQ applied through PCD and SUB, namely 5.8–6.2 \$ m^{-3}. The value derives primarily from fresh tips. The $GEWP_I$ was well above the cost of desalination at \$1.5 m^{-3}. We measured drainage and leaching using fluxmeters. The greatest salt load to groundwater came from BUB, being 135–195 kg m^{-2}. For PCD and SUB it was between 14 and 36 kg m^{-2}. Mass-balance calculations of these salt loadings can predict the impact on the saline quality of aquifers. We used an exemplar loading of 75 kg m^{-2}, and results in an annual salinity rise of 2.6 dS m^{-1} y^{-1} for an aquifer of saturated depth of 100 m. This significant rate of rise in the salinity of groundwater would represent a continuing deterioration in the utility of groundwater.

1. Introduction

The United Arab Emirates (UAE) have a hyper-arid climate with an annual reference evapotranspiration (*ETo*) exceeding 2000 mm (Allen et al., 1998). Rainfall is rare with the annual precipitation averaging around 50 mm y^{-1} (Al-Tamimi et al., 2022). The agricultural, forestry, and landscape sectors account for nearly 60% of the annual water demand across the UAE of 4.2 km^3. Groundwater is relied upon for irrigation of plants of all three sectors, yet the water-tables are falling rapidly, primarily owing to pumping for agriculture, which greatly exceeds the natural recharge rates from the scant rainfall. Sherif et al. (2021) calculated that domestic, industrial, and agricultural activities consume 2854 Mm^3 y^{-1} of groundwater from surficial aquifers across the UAE. They then calculated that the net water-balance for these surficial aquifers is − 1804 Mm^3 y^{-1}. Groundwater quantity is at risk. Furthermore, because of these practices, groundwaters are becoming increasingly saline. Sherif et al. (2021) found that between 1969 and 2015 the quantity of 'fresh' groundwater in the Quaternary aquifers, with electrical conductivities (EC) less than 2 dS m^{-1}, declined from 238 km^3 to just 10 km^3. Over the same period, the volume of 'brackish' groundwaters (2 dS m^{-1} < EC < 25 dS m^{-1}) rose from 136 km^3 to 270 km^3. These changes in aquifer salinities indicate declines in the quality

* Corresponding author.
E-mail address: brent.clothier@plantandfood.co.nz (B. Clothier).

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and utility of groundwaters.

Environment Agency – Abu Dhabi (EAD) has a mandate to conserve groundwater, protect its quality, and to ensure best use of all available waters in the Emirate of Abu Dhabi.

One option to improve the production benefits of irrigation using saline groundwater is for farmers to use stand-alone desalination units to 'freshen-up' groundwater to irrigate high-value crops (Al-Muaini et al., 2019a). Al-Muaini et al. (2019b) found the financial benefit:cost ratio in operational expenses of using desalinated groundwater to irrigate dates was 1.4. Not surprisingly then there has been a rapid growth in small-scale, on-farm desalination units for irrigating of crops (Dawoud, 2017). Private desalination plants are now located on 1150 farms in Abu Dhabi, being 5% of the 25,000 farms in the Emirate (Al-Muaini et al., 2019b).

An Integrated Agri-Aquaculture System (IAAS) has been developed to maximise the value of using brackish groundwater resources coupled with reverse-osmosis desalination technologies (Lyra et al., 2014). Land-based fish-farming uses the reject reverse-osmosis brine (RO brine) from the desalination units, whilst high values crops are irrigated with the 'freshened' groundwater (Sanchez et al., 2015; Somerville et al., 2014). Nutrient-rich aquaculture effluents, known as aquabrine, from the fish tanks are then used to irrigate halophytic crops, for either food, fodder, or seed for grain or for biofuel production (Lyra et al., 2014, 2016; Panta et al., 2014; Robertston et al., 2019). Robertston et al. (2019) carried out a financial analysis of IAAS, and found positive net returns from irrigating *Salicornia bigelovii* Torrey with RO brine. They reported even greater returns for *Salicornia* grown under aquabrine irrigation. Here we extend this benefit:cost analysis to consider the environmental impacts of salt potentially building up in the soil, and the possibility of salt leaching back to the underlying groundwaters (Mohamed et al., 2005).

The aim of our research was to understand the groundwater salinity-impacts and trade-offs through the production benefits of the use of different saline waters to irrigate a halophytic crop. The halophyte we used was *Salicornia bigelovii* Torrey. The fresh tips of the *Salicornia* plant can be harvested as a fresh food-crop known as 'sea asparagus' or 'sea bean' (Al-Yamani et al., 2013; Lyra et al., 2021). *Salicornia* can also be used as dried fodder for animals (Al-Owaimer, 2000), and its seed has a high oil content of more than 25% which can be used to produce a biofuel (Bailis and Yu, 2012). To manage *Salicornia* irrigation sustainably with saline water it is critical to measure the groundwater effects directly to assess better the impacts, options, and opportunities for the use of stand-alone desalination units. In a previous paper (Al-Tamimi et al., 2023) we described modifications to two devices that enabled direct measurement of the soil's water content by time-domain reflectometry (TDR), and monitoring of drainage and leaching via modified passive tension drainage fluxmeters (DFM) (Gee et al., 2009). The top of the convergence ring of the DFMs was set at about 200 mm to avoid the calcareous and gypsic horizon deeper in the soil profile. These modifications made it possible for us to measure the changing patterns of soil water content and to monitor water drainage and salt leaching in this Typic Torripsamment desert soil during our experimental trial with *Salicornia* in 2021/22.

Therefore, the objectives we set out to achieve were to use these measurements to link land management practices to groundwater quality by:

- Quantifying the impact of irrigation waters of different salinities and nutrient contents on the drainage of water and salt leaching to groundwater under *Salicornia* cultivation.
- Measuring the impact of irrigation waters of different salinities and nutrient contents delivered by different irrigation systems on *Salicornia* yields of fresh tips (food), fresh weight (fodder) and dry weight (conserved fodder) and seed weight (oil).
- Determining the water productivity (kg m^{-3}) and economic productivity (\$ m^{-3}) of using saline waters to irrigate *Salicornia* and quantify the environmental impacts of the salt leaching (kg m^{-2}) in the drainage (L m^{-2}) back to groundwater.

2. Materials and methods

2.1. Experimental trials

Our field experiments were carried out at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. As noted, the reference evapotranspiration (ET_o) of Allen et al. (1998) exceeds 2000 mm, whilst the average annual precipitation is around just 50 mm y^{-1}. The year-to-year variation in ET_o is very low, as the weather across the whole of the Arabian Peninsula is generally cloud-free. Precipitation (P) is very rare and is on average less than 2.5% of ET_o. With P/ET_o being less than 3%, the UAE falls within the UNESCO climatic classification of hyper-arid. The average daily-maximum air-temperature exceeds 30ºC for 8 months of the year, and it is above 40ºC for at least two months. The experiments reported in this study are for just one year, namely 2021/2022. We consider this to be agronomically valid in this hyper-arid environment. The weather is uniformly cloud-free, and rainfall is extremely rare and negligible, so the annual trend in the weather is dominated by the seasonal pattern of incident radiation, which is year-wise invariant (Al-Yamani et al., 2018). Inter-annual variation is virtually non-existent.

The soil of the field site is a Typic Torriorthent sandy-skeletal hyperthermic soil (Abdelfattah and Pain, 2012; AD151; Abdelfattah, 2013) with a sand content of over 90% and a bulk density in the range of 1500 – 1600 kg m^{-3}. This is the predominant soil of the Arabian Peninsula. It is a spatially uniform, deep sandy soil of aeolian origin with a carbonatic mineralogy, comprising quartz, mixed sands, volcanic glass, plus calcareous and gypsum concretions at various depths below half a metre (EAD, 2009).

2.2. Crop Agronomy

The *Salicornia* seeds were sown in the second week in November 2021. To enable good germination and establishment, all the plots were irrigated through until 23 February 2022 with low salinity water at 10 dS m^{-1} water. Then three types of saline waters were used for irrigation: aquabrine (AQ; ≈ 40 dS m^{-1}), reverse-osmosis (RO) reject brine from the desalination plant (≈ 40 dS m^{-1}), and groundwater (GW, ≈ 22.5 dS m^{-1}). There were three irrigation systems: bubblers (BUB), pressure-compensated drippers (PCD), and sub-surface tape irrigation (SUB). Irrigation was stopped in mid-August.

Nine separate plots each of 8 m by 8 m were established in a square matrix layout, with 4 m borders between plots. The rows of the matrix were the different water-sources of AQ, RO, and GW. The columns of the matrix were the emitter-device types of BUB, PCD, and SUB. Within each plot, four quadrants, each of 2 m by 2 m, were created, and drainage fluxmeters and vertical TDR probes of length 600 mm were installed near the centre of each quadrant.

The complexity of the irrigation plumbing, and the need to group the devices spatially with data-loggers necessitated the nine four-quadrant plots. As a result, there was only one plot per treatment, albeit with four separate sampling sites near to the center of each quadrant per plot. So strictly this is not replication, but rather a form of pseudo-replication. However, given the spatial uniformity of this ancient desert soil, plus the within-plot uniformity of the irrigation emitters and plumbing, and the lack of weather variability across this exposed site, we take this pseudo-replication as replication in our statistical analyses. The data were analysed using analysis of variance (ANOVA) using Genstat 22nd edition (VSN International, 2022). In the analysis the sub-samples were treated as replicates and a full 2-way factorial model was fitted.

The crop was harvested for the yield of fresh tips on 14 April 2022, total dry weight on 6 June 2022, and for seed during mid-September after irrigation had been stopped in on 31 August, and the crop had

Table 1
Back-transformed means (n = 5) and 95% confidence intervals for the weight of fresh tips of Salicornia bigelovii (g m^{-2}) for each water type and irrigation-emitter type. The original data were log-transformed to equalise the variances. RO is reverse osmosis.

Water type	Device type	Mean	95% C.I.
Groundwater	Bubbler	257	(173, 380)
	Dripper	323	(218, 478)
	Subsurface	253	(171, 375)
Aquabrine	Bubbler	649	(438, 961)
	Dripper	501	(338, 741)
	Subsurface	522	(352, 772)
RO Brine	Bubbler	247	(167, 366)
	Dripper	448	(302, 663)
	Subsurface	517	(349, 766)

then dried off. Crop samples were taken from randomly selected locations within each plot, although locations near to measuring devices were avoided.

2.3. Water Productivity: Irrigation and Economic

The paper by Fernández et al. (2020) provides a clear exposition of water-use nomenclature and irrigation-water productivity definitions. Here we use these definitions. The prime metric of the productive value of irrigation water we take to be irrigation-water productivity, WP_I (kg m^{-3}), being the crop yield (kg m^{-2}) divided by the amount of irrigation water used (IWU, m^3 m^{-2}). As Fernandez et al. (2020) noted this metric can have the limitation in that it does not consider any water supplied by rainfall. But in this hyper-arid region there is essentially no rainfall, so the metric of WP_I is appropriate (Al Tamimi et al., 2022).

For our assessment of the economic value of the irrigation waters, we take a slight variant of the Gross Economic Irrigation-Water Productivity, $GEWP_I$ (\$ m^{-3}). For the numerator in this metric, Fernandez et al. (2020) used the Gross Margin (\$ ha^{-1}), being the revenue minus variable costs. Because we are not dealing with an actual farm, but rather experimental plots, there is little practical relevance for the costs we incurred during production. So here, we simply take the numerator to be the revenue received for the products (\$ ha^{-1}). The denominator is the amount of irrigation used (IWU m^3 m^{-2}) to produce the products for which the revenue would be received.

Our simple benefit-cost assessment compares the $GEWP_I$ with the direct operational-expenses to produce desalinated water. We consider the cost of desalination to be US\$1.5 (± 0.25) m^{-3}, as given by the company Advisian for small desalination plants (https://www.advisian.com/en/global-perspectives/the-cost-of-desalination). At the current exchange rate, this translates to AED 5.5 (± 0.9) Arab Emirati Dirhams m^{-3}. At this stage we have not considered the economic value that would come from the use of the desalinated water to grow high-value crops such as vegetables and dates, nor are we considering the revenues that would come from aquacultural production. That future analysis will await a full economic analysis of the entire system, which will include an assessment on the other side of the ledger resulting from the costs of environmental degradation as a result of the salt leachate from the *Salicornia* down to the groundwater resource.

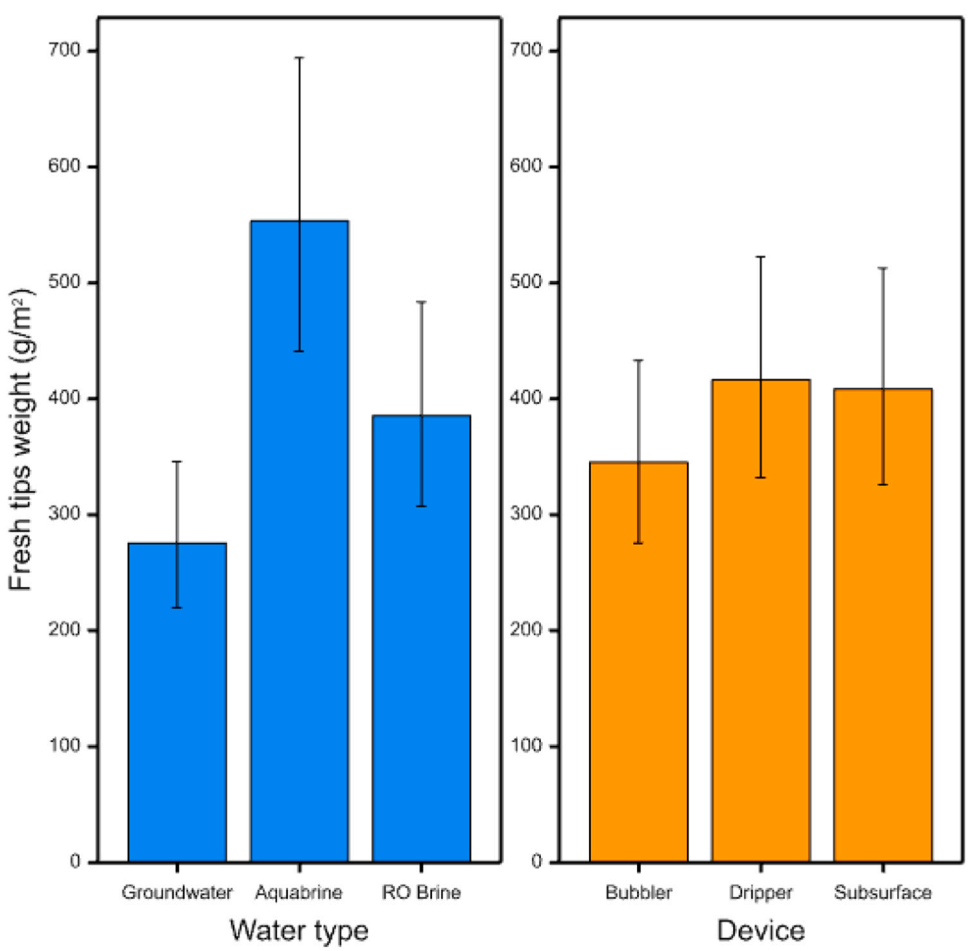

Fig. 1. Mean back-transformed weight of *Salicornia bigelovii* fresh tips in g m^{-2} for the three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubblers, pressure-compensated drippers, and subsurface tape. The errors bars are 95% confidence limits for the mean ($n = 15$). The original data were log-transformed to equalise the variance.

Table 2
Means ($n = 5$) for fresh weight yield of *Salicornia bigelovii* (kg m^{-2}) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 0.807. RO is reverse osmosis.

	Water source		
Device type	Groundwater	Aquabrine	RO Brine
Bubbler	11.07	16.62	13.33
Dripper	6.82	7.12	5.96
Subsurface	5.18	7.67	5.04

2.4. Statistical Analyses

Residual plots of all of the crop-yield datasets were checked for normality and homoscedasticity. To equalise the variances across the various irrigation water-sources and emitter devices for statistical treatment by analysis of variance (ANOVA) using Genstat (VSN International, 2022), the original fresh-tip yield data were log-transformed. For the crop-harvest yields and the seed yield data, there was no need to log-transform the data prior to the ANOVA procedures.

3. Crop growth and yields

The crop yields are presented in terms of fresh tips for food value (Section 3.1), dry weight for the value of fodder (Section 3.2), and seed yield for the potential value as biofuel, or fodder (Section 3.3).

3.1. Fresh-tip yields

The yields of the young, fresh tips harvested for food from the top 200 mm of the canopy are presented in Table 1 and Fig. 1. The back-transformed means are presented in Table 1 along with the 95% confidence limits. The fresh-tip yields ranged from 247 g m^{-2} for RO applied through BUB, up to 649 g m^{-2} for AQ and BUB.

The groupings of the means of the fresh-tip yields by water source and emitter device are given in Fig. 1.

There was a significant effect of water type ($F=9.74$, $df=2,36$, $p < 0.001$), but no significant effect ($P > 0.05$) of irrigation device type ($F=0.85$, $df=2,36$, $p = 0.43$) on the yields of fresh tips. There was no significant interaction ($F=2.12$, $df=4,36$, $p = 0.10$) between the effects of water source and device on the fresh-tip yields.

3.2. Crop harvest yields

We present the crop harvest yields as both fresh weights and dry weights, since the harvested *Salicornia* could be fed straightaway as fresh forage to animals or conserved as dry forage for later feeding to stock.

3.2.1. Fresh weight yield

The means of the fresh-weights for each water source and irrigation emitter are given in Table 2.

Fig. 2 presents these fresh-weight yields grouped by water type and emitter device.

There was a significant effect of water source ($F=10.4$, $df=2,36$, $p < 0.001$) and irrigation-emitter type ($F=84.0$, $df=2,36$, $p < 0.001$).

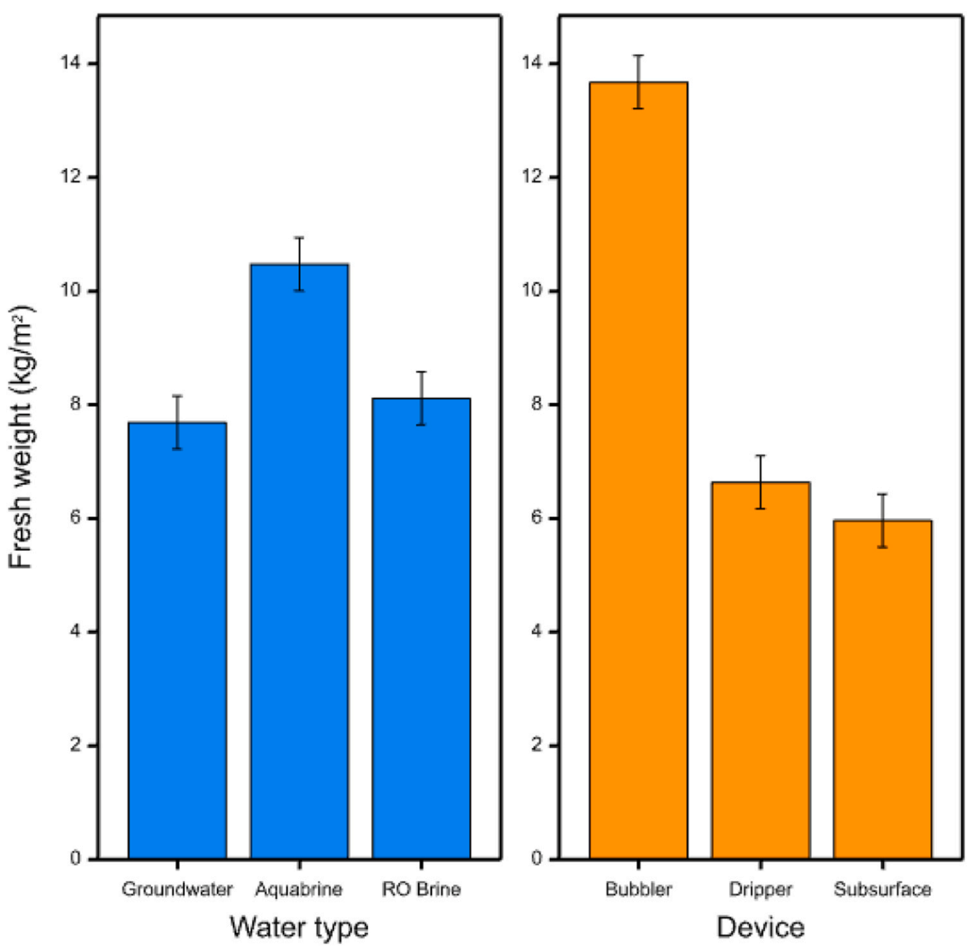

Fig. 2. Mean *Salicornia bigelovii* fresh-weight yield in kg m^{-2} for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean ($n = 15$).

Table 3
Mean (n = 5) for dry-weight *forage* yield *of Salicornia bigelovii* (kg m^{-2}) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 0.19. RO is reverse osmosis.

	Water Source		
Device type	Groundwater	Aquabrine	RO Brine
Bubbler	1.98	2.58	2.34
Dripper	1.49	1.55	1.36
Subsurface	1.32	1.61	1.11

The yields were the highest for AQ and BUB. There was a significant interaction between the effects of water sources and emitters (F=2.76, df=4,36, p = 0.042) on the fresh-weight yields.

3.2.2. Dry weight yield

The dry-weight yields are presented in Table 3 arranged by water source and emitter type.

These data are presented in Fig. 3 when grouped by the means of water source and device type.

For dry-weight yields, unlike fresh-weight yields, there was a tendency for an effect of water type (F=2.84, df=2,36, p = 0.072), albeit a significant effect of irrigation device type (F=22.8, df=2,36, p < 0.001). Again, the highest yields were realised by AQ and BUB. But here there was no significant interaction (F=0.93, df=4,36, p = 0.46) between the effects of water sources and emitters on dry-weight yield.

3.3. Seed yields

The seed weights in g m^{-2} are presented in Table 4 by water source and emitter type.

The seed-yield means are presented in Fig. 4 grouped by water type and emitter device.

For the seed yields there was a significant effect of water type (F=8.22, df=2,36, p = 0.001) and a significant effect of irrigation device type (F=6.52, df=2,36, p = 0.004). The highest yields were achieved using AQ and PCD. However, here there was no significant interactions (F=1.24, df=4,36, p = 0.31) between the effects of water sources and emitters on seed weight.

3.4. Water Productivity Results and Discussion

3.4.1. Water Productivity

These yield results provide valuable data from which we can

Table 4
Mean (n = 5) for seed weight of *Salicornia bigelovii* (g m^{-2}) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 15.3. RO is reverse osmosis.

	Water source		
Device type	Groundwater	Aquabrine	RO Brine
Bubbler	153.7	157.4	116.2
Dripper	131.6	162.8	122.2
Subsurface	132.0	115.6	57.4

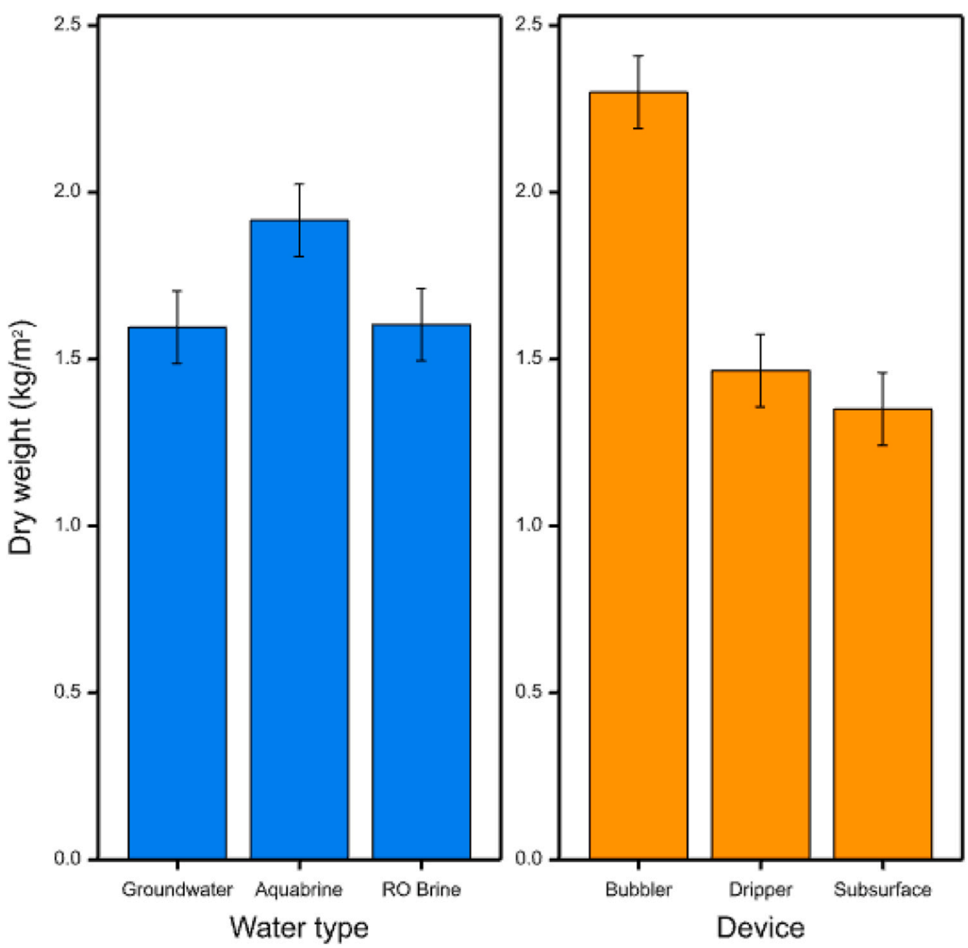

Fig. 3. Mean *Salicornia bigelovii* dry-weight yield in kg m^{-2} for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean (n = 15).

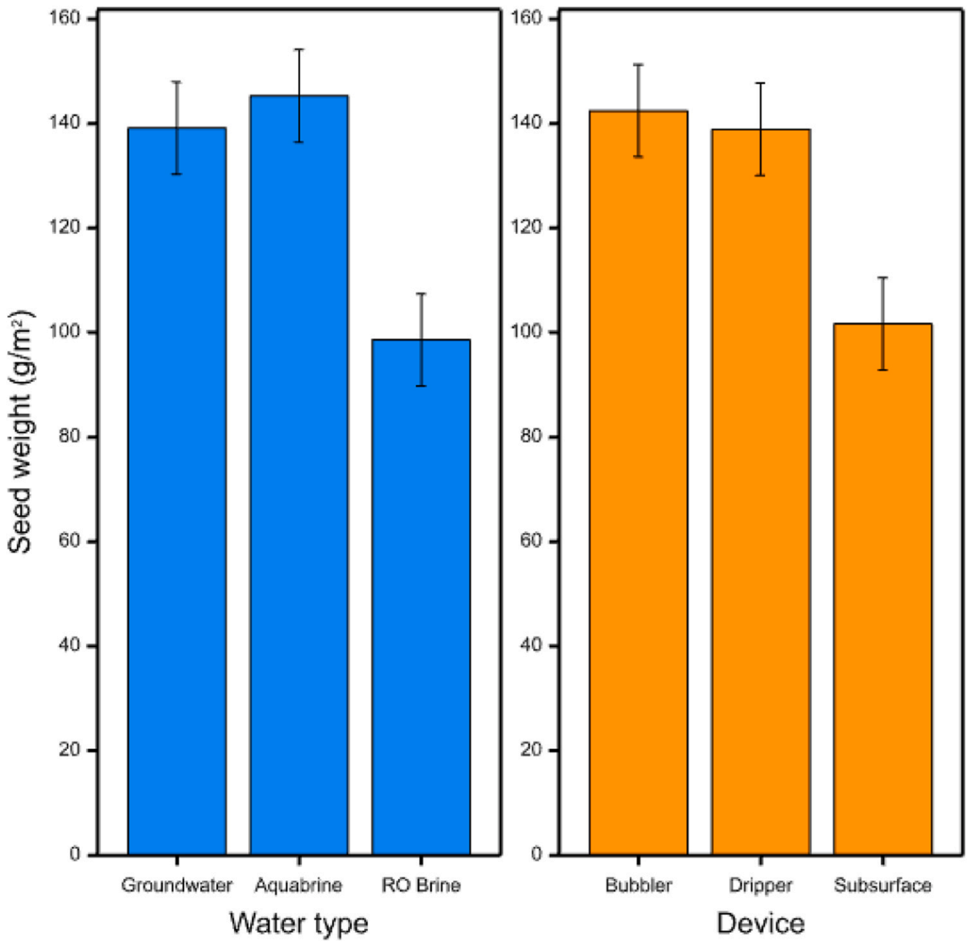

Fig. 4. Mean *Salicornia bigelovii* seed-weight yield in g m^{-2} for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean ($n = 15$).

Table 5
The amount of irrigation water added in L m^{-2} to produce the fresh tips of *Salicornia bigelovii* harvested on 14 April 2022, and the irrigation total added in L m^{-2} to produce the final dry yield for forage and seeds harvested in mid-September. Irrigation ceased on 31 August. RO is reverse osmosis.

Emitter	Fresh-Tips: Water Added (L m^{-2}) - Up to 14 April		
	Groundwater	Aquabrine	RO Brine
Bubbler	4171	4193	3889
Dripper	1251	1412	1333
Subsurface	1336	1590	1420
	Forage & Seed: Water Added (L m^{-2}) - To Mid-September		
Bubbler	8056	8243	7522
Dripper	2730	2506	2669
Subsurface	2523	2791	2489

determine the irrigation productivity (WP_I, kg m^{-3}) of the various water sources and emitter types.

In Table 5 we present the irrigation-water used (IWU, L m^{-2}) for each water source and emitter type in the production of fresh tips, plus dry forage, and seed. In that calculation, we have not considered the harvesting of the *Salicornia* for fresh forage for direct feeding to animals. Thus, the total IWU for forage and seed is the amount of irrigation water used up until the cessation of irrigation on 31 August.

In terms of the IWU with our scheduling, the bubblers used two to three times the amount of water than either the drippers or subsurface devices. This total IWU was applied to obtain fresh-tip yields plus those from the forage and seed yields. The amount of water used through to fresh-tip harvest in April was about half of that applied for the whole season. Some 8000 L m^{-2}, or 8000 mm, of water was applied in total through the BUB system. The annual reference evapotranspiration, ET_o, for this region is just 2000 mm (Al-Tamimi et al., 2022). The schedules for the PCD and SUB were better aligned with ET_o. Thus, we have created a wide range of salt-leaching fractions through our experimental designs. This is advantageous as it enables us to provide a wide assessment of both water productivities and salt-leaching impacts.

The values found for water productivity WP_I (kg m^{-3}) are given in Table 6 for the three water sources and emitter types for the yields of fresh tips, dry forage, and seed. Despite BUB producing the highest yields, the scheduling we used with these devices resulted in the lowest WP_I values, being about 58% of those for PCD, and 52% for SUB. The WPI for dry forage was between 1.4 and 2.8 kg m^{-3} (Table 6). Not surprisingly this is much lower than the WPI of 4–7 kg m^{-3} found by Al Tamimi et al. (2022) for outdoor vegetables grown in the UAE using fresher groundwater. The WP_I here for *Salicornia* under saline irrigation is somewhat higher that the 0.5–1.3 kg m^{-3} found by Li et al. (2016) for cereals growing in the hyper-arid Hexi Corridor in Northwest China. Our WP_I was also higher than that of 1 kg m^{-3} found by Al-Muaini et al. (2019b) for dates growing in the UAE with saline irrigation water using a salt-leaching fraction of 25%.

Our results show the positive value for production of using saline waters to grow *Salicornia* for fresh-tips, forage, and seed. The highest water productivities WP_I across all three crop-output types came from aquabrine applied by pressure-compensated drippers (Table 6).

3.4.2. Economic Water Productivity

We now use these WPI values to assess the gross economic water-

Table 6
Left. The irrigation-water productivity (kg m^{-3}) for the harvest of fresh tips, dry forage, and seeds of *Salicornia bigelovii* in relation to water source and emitter type. Right. The gross economic productivity in US\$ m^{-3} fresh tips, dry forage, and seed assuming the price for fresh tips to be US\$15 kg^{-1} and US\$0.3 kg^{-1} for dry forage and seed. The table on the bottom right is for the combined revenue from all products. Here 1 AED Arab Emirati Dirham is assumed to be US\$ 0.27. Here gross economic productivity considers only gross revenue, not gross margin. RO is reverse osmosis.

	WP_I, Irrigation-Water Productivity (kg m^{-3})				$GEWP_I$, Gross Economic Irrigation-Water Productivity (\$ m^{-3})		
Fresh tips	Groundwater	Aquabrine	RO Brine	**Fresh tips (\$15 kg^{-1})**	Groundwater	Aquabrine	RO Brine
Bubbler	0.06	0.15	0.06	Bubbler	0.92	2.32	0.95
Dripper	0.26	0.35	0.34	Dripper	3.87	5.32	5.04
Subsurface	0.19	0.33	0.36	Subsurface	2.84	4.92	5.46
Dry forage				**Dry forage (\$0.3 kg^{-1})**			
Bubbler	1.37	2.02	1.77	Bubbler	0.41	0.60	0.53
Dripper	2.50	2.84	2.23	Dripper	0.75	0.85	0.67
Subsurface	2.05	2.75	2.02	Subsurface	0.62	0.82	0.61
Seed	WP_I, Irrigation-Water Productivity (g m^{-3})			**Seed (\$0.3 kg^{-1})**			
Bubbler	0.02	0.02	0.02	Bubbler	0.0001	0.0001	0.0000
Dripper	0.05	0.06	0.05	Dripper	0.0001	0.0002	0.0001
Subsurface	0.05	0.04	0.02	Subsurface	0.0002	0.0001	0.0001
					$GEWP_I$, Gross Economic Irrigation-Water Productivity (\$ m^{-3})		
				Tips, Forage & Seed	Groundwater	Aquabrine	RO Brine
				Bubbler	1.34	2.93	1.48
				Dripper	4.62	6.17	5.71
				Subsurface	3.46	5.75	6.07

productivity values $GEWP_I$ (\$ m^{-3}) (Fernández et al., 2020). As we have noted above, our $GEWP_I$ varies slightly from that of Fernandez et al. (2020) because we consider only gross revenue, not gross margin.

Robertson et al. (2019) noted that there are very few reports on the market value of *Salicornia* as a fresh-tip vegetable crop. In their analyses they assumed a price of \$4.73 kg^{-1}. However, a market survey shows that fresh Salicornia sold as either 'sea asparagus' or 'sea bean', can fetch prices of over \$20 kg^{-1}. We simply take the value of the fresh tips here to be \$15 kg^{-1}. Robertson et al. (2019) also assessed the value of *Salicornia* as a forage crop on a nutritional comparison with the forage crops of Rhodes grass and alfalfa. Given the lower nutritional value of *Salicornia* they reckoned the forage value to be \$300 t^{-1}. We use that value here for the gross revenue from *Salicornia* forage. Estimation of the revenue generated from the sale of seed for biofuels is even more challenging. Alassali et al. (2013) estimated the price of *Salicornia* seed for a bio-refinery to be up to \$0.05 kg^{-1}. Fredsgaard et al. (2021) assigned zero value to the *Salicornia* feedstock, considering it to be a waste product after food production. Here, we take the value of the seed to be the same, on a dry weight basis, as that of the dry forage, namely \$0.3 kg^{-1}. This is because even if the seed were not used for biofuel, it could still form part of the conserved forage-feed to animals.

The $GEWP_I$ values for the three water types, emitter devices and harvest categories are provided on the right in Table 6. The greatest values of around 1–5 \$ m^{-3} are for fresh tips, especially under PCD and SUB for AQ and RO. The lowest values for fresh tips are for the production using BUB. The $GEWP_I$ for dry forage is about 15% that of fresh tips, ranging from 0.4 to 0.9 \$ m^{-3}. The $GEWP_I$ values for seed production are small because of the low price set for seed, and the low productivity of seeds. The overall $GEWP_I$ values summed for all the crop outputs are highest for PCD and SUB, with only a small variation between water types, namely 2.5–6.2 \$ m^{-3}.

The $GEWP_I$ values are dominated by the price received for the fresh tips. This value could be even further enhanced if there were sequential, multiple harvests for fresh tips. Multiple fresh-tips harvests would have additional advantages. We noticed that those sections of the crop that had undergone a fresh-tip harvest were less likely to lodge. In those areas not harvested, the crop grew taller and eventually lodged, thereby diminishing the harvest quality of the forage. As well, producing more food for human consumption would support the UAE's goal for increased food security (Shahin, Salem, 2015; UAE, 2019).

The company Advisian considered the current operating costs of desalination plants to be \$1.5 ($\pm$ 0.25) m^{-3} (https://www.advisian.com/en/global-perspectives/the-cost-of-desalination). The revenue benefits from *Salicornia* production alone would be greater than these operating costs for the desalinated water-resources from AQ and RO, and for both the emitter types of PCD and SUB (Table 6). The $GEWP_I$ values for all desalinated waters using BUB are below the operating costs of desalination units, despite the BUB yields being higher.

4. Drainage and Leaching

The groundwater resources of Abu Dhabi are hugely valuable. Baker and van Houtven (2015) carried out an economic quantification of the net present-value of groundwater in Abu Dhabi resulting from its combined utility for agriculture, forestry, amenity and strategic value. They found the net present-value Abu Dhabi's groundwater to be US\$ 272 billion (AED 781 billion at 1 AED = \$0.272) for 3% discount rate, and \$120 billion (AED 443 billion) at an 8% discount rate. Groundwater in this hyper-arid region is a highly valuable natural capital stock well worth protecting, not only interms of quantity, but also in relation to its salinity which could compromise its utility.

4.1. Drainage

Drainage below the rootzone provides for the recharge of groundwater. The need for a salt-leaching fraction means that there will be drainage through the rootzone of all the *Salicornia* plots. There were four passive-tension drainage fluxmeters (DFM) within each plot. The weekly drainage results, in mm d^{-1}, from these 36 DFMs are shown in Fig. 5 grouped by emitter type and water source.

Owing to the spatial variability in the drainage measurements, we could not be sure that our measured drainage values would provide mass-balance closure in relation to the inputs of irrigation water, and the outputs of crop evapotranspiration losses. We decided to infer the drainage component through mechanistic modelling of the water balance. This was done to ensure that our drainage fulfilled mass-balance closure. The key process in our water-balance model is that of the crop evapotranspiration ET_C. Drainage is then calculated as the residual, given that on a daily basis our time-domain reflectometry measurements showed there was no net daily change in the water content of the rootzone once the irrigation scheduling began. We adopted an FAO56 approach to modelling ET_C using the crop-coefficient K_C methodology we have outlined in Al-Tamimi et al. (2022). The modelled drainage results (L m^{-2}) are presented in Table 7 alongside the amount of

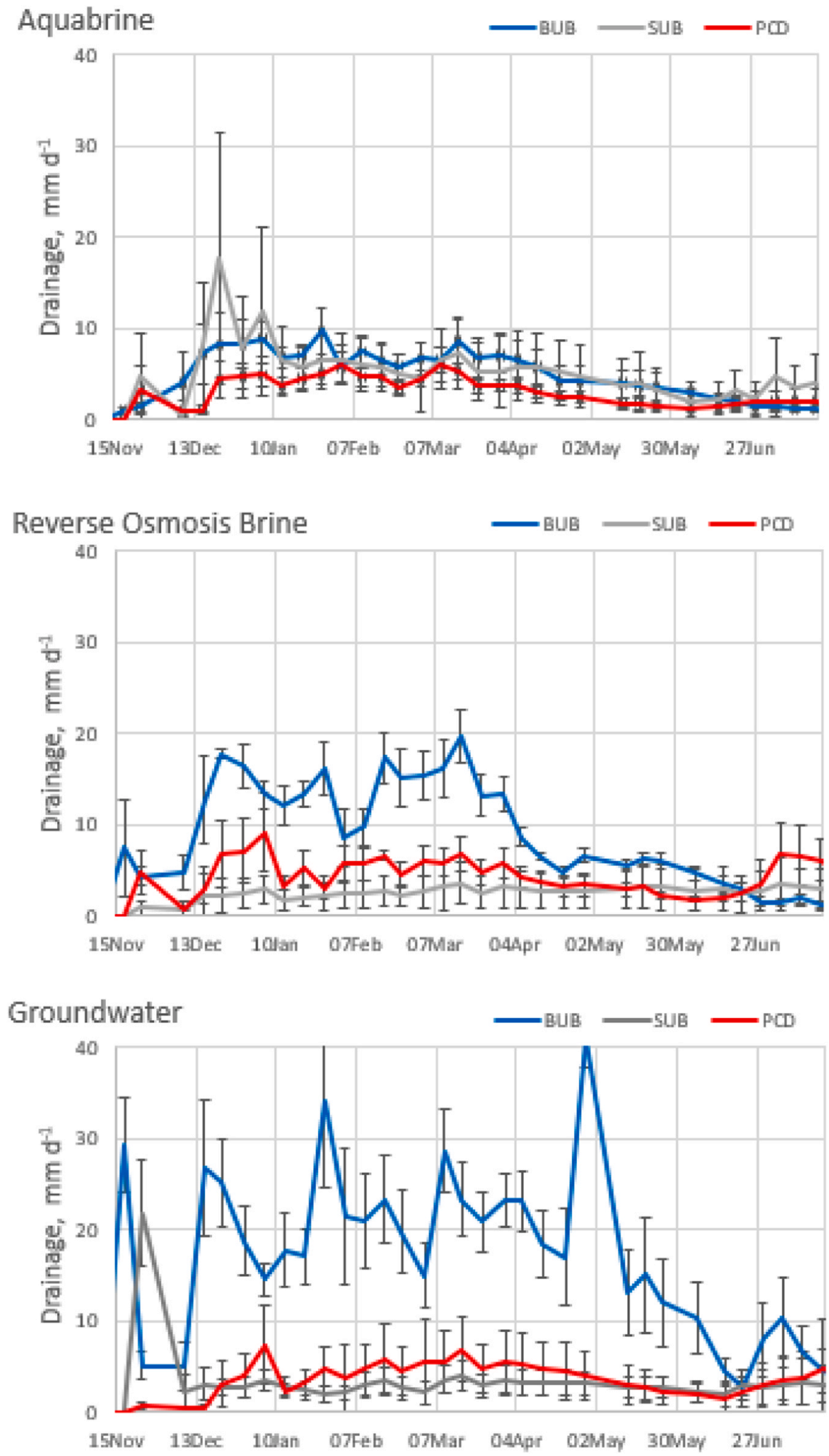

Fig. 5. The drainage (mm d^{-1}) measured under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by tension drainage fluxmeters under three different irrigation emitter types (BUB, bubbler; SUB, subsurface; PCD, pressure-compensated dripper) with aquabrine (top), reverse osmosis water (middle) and groundwater (bottom). The bars represent the standard errors of the measures from 4 drainage fluxmeters (DFMs) for each emitter type.

irrigation (L m^{-2}) applied by the various emitter devices for each water type.

The amount of drainage was highest under the BUB devices and ranged between about 5500 and 6200 L m^{-2}, being about three-quarters of the total irrigation water applied by the bubblers. The drainage under the PCD and SUB emitters was lower, both in terms of amount, being between about 800 and 1600 L m^{-2}, and also as a percentage of the irrigation amount applied, which ranged between 30% and 60%.

The irrigation strategies employed here have provided a high degree of groundwater recharge, with recharge being between 30% and 75% of the water drawn originally from groundwater to irrigate the *Salicornia*.

Table 7
The modelled drainage (L m^{-2}) in relation to the amount of irrigation water applied (L m^{-2}), along with the calculation of the leaching fraction *LF* (Eq. 1). The EC (dS m^{-1}) of the applied waters, EC_w, are given for the three water sources, and the predicted EC of the drainage water, EC_{dw}, (Eq. 2) is given along with that average measured by the drainage fluxmeters from weekly measurements between May and August for the three waters and three emitter types. RO is reverse osmosis.

Water Source	Emitter-Type	Drainage, L m^{-2}	Water Applied, L m^{-2}	Leaching Fraction	ECw, dS m^{-1}	Predicted ECdw, dS m^{-1}	Measured* ECdw, dS m^{-1}
Aquabrine	Bubbler	6231	8366	0.74	40	53.7	75.4
	Dripper	1059	2630	0.40	40	99.3	88.2
	Sub-surface	1666	2915	0.57	40	70.0	52.8
RO Brine	Bubbler	5498	7646	0.72	40	55.6	71.5
	Dripper	817	2768	0.30	40	135.5	71.6
	Sub-surface	1146	2612	0.44	40	91.2	45.6
Groundwater	Bubbler	6021	8179	0.74	25	34.0	53.7
	Dripper	927	2854	0.32	25	77.0	58.6
	Sub-surface	1159	2647	0.44	25	57.1	31.2
					Average	74.8	61.0

* Average of weekly measurements during May-August

4.2. Leaching

The electrical conductivities (EC, dS m^{-1}) in the leachates measured weekly by the DFMs are shown in Fig. 6. The measurements began with irrigation after the seeds were sown in early November 2021. Up until late February 2022, all the plots were irrigated with low salinity water with an EC of 10 dS m^{-1} to ensure good germination and successful early seedling growth of the *Salicornia*. Then the irrigation sources were shifted to AQ and RO at 40 dS m^{-1}, plus GW at 25 dS m^{-1}. The leachate values responded immediately to these changes in the salinity of the irrigation waters. During this early stage of crop growth, with ET_C being low, the EC values of the leachates were essentially those of the applied irrigation waters. However, as the crop grew and ET_C became a more significant component of the water balance, there were rises in the EC values of the leachates, and eventually the leachate ECs exceeded those of the applied waters.

Ayers and Westcot (1994) noted that for a leaching fraction, *LF*, defined as

$$LF = \frac{Depth \quad of \quad water \quad leached \quad below \quad the \quad rootzone}{Depth \quad of \quad irrigation \quad water \quad applied} \tag{1}$$

the EC in leachate, EC_{dw}, will then be given by

$$EC_{dw} = \frac{EC_w}{LF} \tag{2}$$

where EC_w is the EC of the applied water. The lower the *LF*, with less water draining through the profile, the higher the relative EC in the leachate.

In Table 7 we list the seasonal LF values for the various water sources and emitter types. As noted above, the LFs for the BUB devices were higher (≈0.7) than those for the PCD (≈0.35) and SUB (≈0.5). Using the LF and EC_w values we can use Eq. 2 to predict the EC values in the leachates, EC_{dw} (Table 7). The predicted EC_{dw} values are in consistent agreement with those measured by the DFMs during the major period of crop growth between May and August (Table 7). Across all water sources and emitter types the average predicted EC_{dw} is 74.8 dS m^{-1}, and our DFMs measured a somewhat similar value of 61 dS m^{-1}.

Irrigating halophytic crops with saline waters requires that there be a salt leaching-fraction LF to ensure that salts left in the rootzone after ET_C are flushed out to prevent a build-up of salt in the soil of the rootzone. When a crop uses some portion of the applied water, the LF will be less than unity. So when this LF is less than one that means that the leachate EC_{dw} in the drainage water will be at a higher concentration than that in the applied water, and this loading of salt could have deleterious impacts, over time, on the quality of the underlying aquifer through this groundwater recharge.

5. Salt-Leaching Impacts

The mass-balance calculations of the salt added annually across the nine plots of three water sources and three emitter types ranged from 36 to 164 kg m^{-2}, and the salt loss measured by the DFMs went from 18 to 195 kg m^{-2} (Table 8). The average amount of salt added across all nine plots was 80 kg m^{-2}, and the amount we measured that was lost by leaching in the upper part of the rootzone was on average 70 kg m^{-2}. We estimate that over the growing season there is a storage change of salt in the soil profile down to 120 cm of around 2–4 kg m^{-2}, as this would represent the salt retained after the initial flushing with the 10 dS m^{-1} water that was used to enable good germination and early seedling growth. Within the constraints posed by the spatial variability in our leaching measurements with the DFMs, there is reasonable mass-balance agreement with the applied loads and those measured leaching through the soil profile with our fluxmeters.

We next assessed what the impact of these leachate loadings of salt mean for the water quality of the underlying aquifer. Let the annual loading of salt be designated L (kg m^{-2}). We consider the underlying aquifer to be of saturated thickness d (m), and we take the volumetric saturated water content of the aquifer to be θ (m^3 m^{-3}). So, the areal volume of water in the aquifer is $\theta.d$ (m^3 m^{-2}).

We now consider the impact of the annual loading of the salt leachate on the underlying aquifer's water quality. The descending salt front will be denser than the resident soil solution underneath, and this could create Rayleigh-Taylor instabilities that might lead to fingering and plumes as the heavier salt-solution travels preferentially downwards (Bear, 1972). This plume of the denser leaching front of higher salinity might then descend to the aquifer rapidly with far-reaching consequences that would preferentially impact the area directly under the irrigated plots. This is most likely where the wells used for irrigation are to be located. In such cases there would be a localised short-circuit between well extraction, salt leaching, and the degradation in aquifer water quality. To carry out a detailed risk assessment of the impact of salt leaching would, under such circumstances, be difficult in the absence of information about the dimensions of the fingering plumes. Here we take a simpler and more conservative approach.

We simply assume that the leachate from above will quickly and fully equilibrate with the resident water by gravity mixing with the heavier incoming leachates. Mass balance then determines that the annual rise in the salt concentration of the aquifer, ΔC (kg m^{-3}), will be $L\ (\theta.d)^{-1}$. The relationship between the EC of a solution and C can be written EC $= \varepsilon.C$ (dS m^{-1}), where we take here ε to be 0.72 kg m^{-3}/(dS m^{-1}). Therefore, the annual rise in the EC of the aquifer due to the salt loading from above would be $\Delta EC = L\ /\ (\varepsilon.\ \theta.d)$ in dS m^{-1} y^{-1}. This can be applied locally, and here we provide an exemplar calculation. The Groundwater Atlas of the Emirate of Abu Dhabi shows that the saturated thickness of the aquifer in the western Al Dhafra region is of the order of 100 m, whereas close to Al Ain, under the lee of the Omani Mountains,

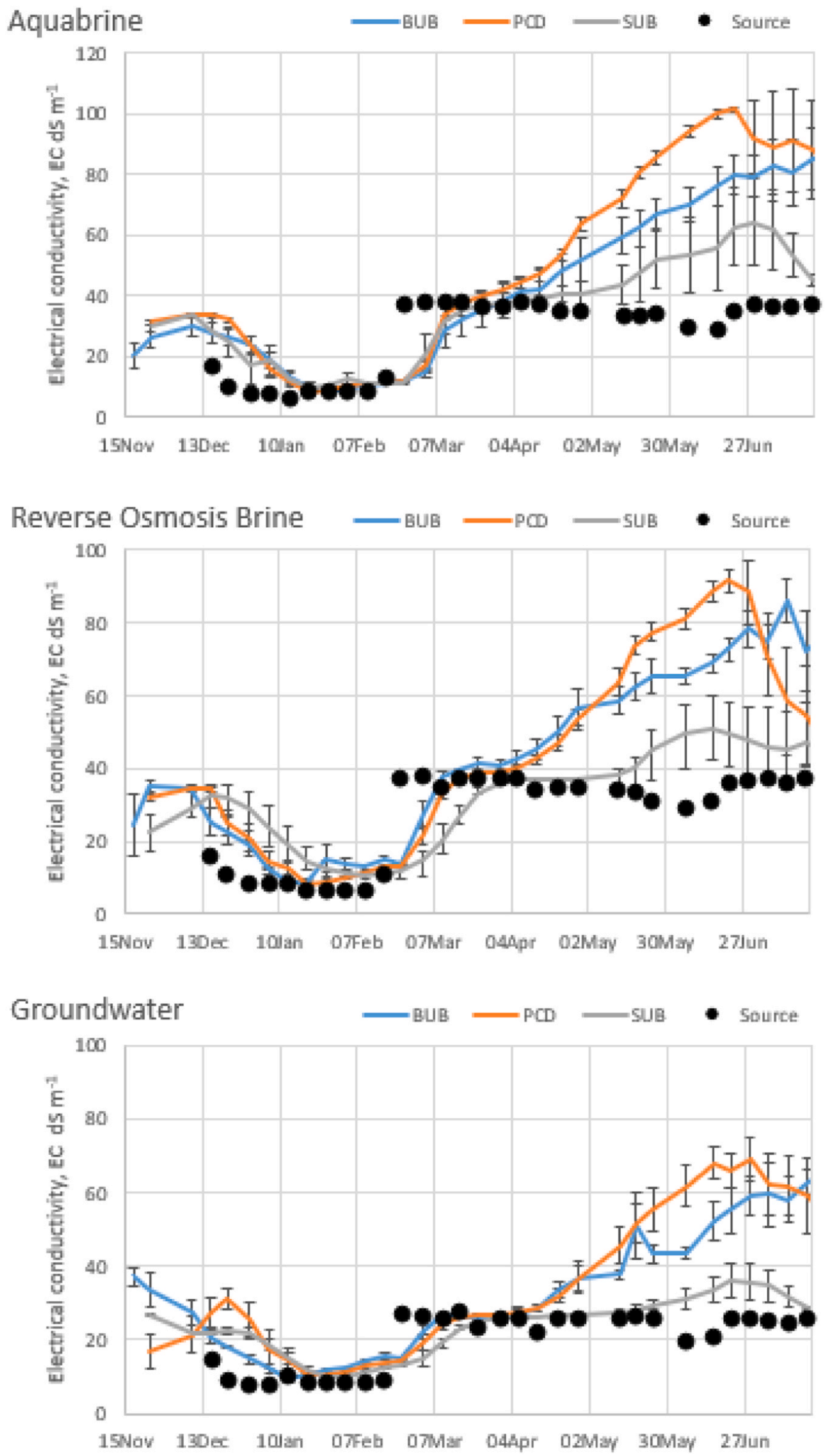

Fig. 6. The electrical conductivity (EC, dS m^{-1}) of the leachate measured in drainage under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by tension drainage fluxmeters under irrigation with aquabrine (top), reverse osmosis (RO) water (middle) and groundwater (bottom). The switch between low salinity irrigation to RO water was on 23 February 2022. The original irrigation was water at EC at 10 dS m^{-1}, and then under aquabrine and reverse osmosis brine at about 40 dS m^{-1}, and groundwater at 25 dS m^{-1}. The bars represent the standard errors of the measures from 4 drainage fluxmeters (DFMs) for each emitter type.

d can exceed 400 m (EAD, 2018). Our time-domain reflectometry measurements (Al-Tamimi et al., 2023) show that $\theta \approx 0.4$. Taking here for heuristic purposes $d = 100$ m, and the average loading L of 75 kg m^{-2} (Table 8), means that the annual rise in groundwater salinity would be $\Delta EC \approx 2.6$ dS m^{-1} y^{-1}. This is a large impact indicating significant degradation in the water quality of the underlying aquifer through the salt loading as a result of the LF being less than unity.

In 2014, the Emirati Ministry of Environment and Water (MOEW, 2014) presented a map of the rise in the salinity of groundwaters in the UAE. For the crescent oases surrounding Liwa in the Al Dhafra region, and along the western flanks of the Omani Mountains the rise in groundwater salinity between 1996 and 2012 was about 1–2 dS m^{-1}. Intensification of land-use using saline groundwater, with the required leaching fraction LF < 1, will accelerate the saline degradation of these aquifers. Our current work is focussing on an economic valuation of the environmental impacts of this salt loading and exploring solutions, so

Table 8
The salt added in the irrigation water for the three emitter-device types of bubbler (BUB), dripper (PCD) and subsurface tape (SUB) for each of the three waters aquabrine (AQ), reverse osmosis brine (RO) and groundwater (GW), in relation to the leachate losses of salt measured by the tension drainage fluxmeters. The measured losses were calculated using the measured electrical conductivity in the leachate, and the modelled drainage. Modelled drainage (Al Tamimi et al., 2022) was used because of the high variability in the measured values (Fig. 5).

Water Source	Emitter-Type	Salt Added, kg m^{-2}	Measured Salt Loss, kg m^{-2}
Aquabrine	Bubbler	164.4	195.0
	Dripper	48.8	23.3
	Sub-surface	53.2	36.1
RO Brine	Bubbler	152.7	169.3
	Dripper	52.6	13.6
	Sub-surface	45.9	22.3
Groundwater	Bubbler	120.1	135.0
	Dripper	42.2	21.0
	Sub-surface	36.4	17.8
	Average	79.6	70.4

that we can assess the benefit:cost ratios of the various ways to use saline waters to provide foods, forages, and fuels.

At this stage, we now know the valuable economic water productivity of GEWP$_I$ (\$ m^{-3}) when irrigating the halophytic crop *Salicornia* with saline waters. We have also determined the biophysical environmental impact in terms of the rise in the salinity of the underlying aquifers due to the loadings of salt in the leachates. The challenge now is to quantify the change in value of the ecosystem services supplied by groundwater because of these increases in salinity resulting from the productive growth of halophytic crops using saline waters.

6. Conclusions

We have described our experiments using three types of saline waters to irrigate the halophytic crop of *Salicornia* in the hyper-arid United Arab Emirates. The three waters were GW at 25 dS m^{-1}, RO from a desalination unit at 40 dS m^{-1} and AQ being the effluent from land-based aquaculture producing fish in tanks filled with RO brine, again at 40 dS m^{-1}. These three waters were applied through BUB, PCD, and SUB. The reference ETo at our site was of the order of 2000 L m^{-2} (2000 mm). Our irrigation schedule for BUB applied around 8000 L m^{-2}, and for PCD and SUB about 2600 L m^{-2}.

The yields of harvest forage were greatest for BUB being 2.0–2.6 kg m^{-3} compared to 1.1–1.6 kg m^{-3} for the other emitter devices (Table 3). However, the water productivities WPI (kg m^{-3}) for forage were greatest for PCD and SUB being 2.0–2.8 kg m^{-3} for all waters across, whereas for BUB ranged from 1.4 to 2.0 kg m^{-3} (Table 6). We then carried out an assessment of the gross economic water productivity (GEWP$_I$, \$ m^{-3}) based solely on gross revenue. For the total putative revenue from fresh tips, forage, and seeds, we found the GEWP$_I$ to be highest for AQ applied through PCD and SUB, namely 5.8–6.2 \$ m^{-3} (Table 6). This is well above the presumed cost of desalination at \$1.5 m^{-3} and this does not consider the additional value that would come from the saline groundwater freshened by desalination for irrigation of high value crops, or from the fish grown in the aquaculture tanks. The BUB had the lowest GEWP$_I$ of between 1.3 and 2.9 \$ m^{-3}. We conclude that the greatest economic benefit for halophyte production, balanced for water usage, would come from fresh tips grown with AQ applied through either PCD or SUB. This value could be further enhanced through multiple harvest for fresh tips.

The GW had a salinity of 25 dS m^{-1}, whereas the RO and AQ were at 40 dS m^{-1}. The leaching fractions LF were about 0.72–0.74 for BUB, and 0.3–0.6 for PCD and SUB. Given the irrigation scheduling, the greatest salt load to groundwater came from BUB, being 135–195 kg m^{-2}. For PCD and SUB it was less, between 14 and 36 kg m^{-2}. We then carried out simple mass-balance calculations of the biophysical impacts that these salt loadings would have on the saline quality of the underlying aquifers. In our simple model, we used an exemplar loading of 75 kg m^{-2}, and this we found would result in an annual salinity rise of 2.6 dS m^{-1} y^{-1} for an aquifer of saturated depth of 100 m. This would be a significant rate of rise in the salinity of groundwater and represents a deterioration in the utility of the subterranean water reserves. Our next task is to carry out an economic assessment of the changed value in the groundwater resources through the diminished ecosystem services delivered by the increased salinity. This will be compared with the now-known value that comes through the gross economic water productivity, GEWPI, which we have found here for the production of *Salicornia* irrigated by saline waters in this hyper-arid region.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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