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Water requirements for cultivating *Salicornia bigelovii* Torr. with seawater on sand in a coastal desert environment

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The forage and oilseed halophyte, *Salicornia bigelovii* Torr., was grown in gravity-drained lysimeters set in open plots of the same crop over two seasons in a coastal desert environment in Sonora, Mexico. The lysimeters were irrigated daily with seawater (40 g l^{-1} salts) at rates ranging from 46–225% of potential evaporation. Biomass and seed yields increased with increasing irrigation depth over the range of treatments. Biomass yields ranged from 13·6–23·1 t DM ha^{-1}, equivalent to conventional forage crops, on seasonal water application depths of 2·3–3·8 m, but were markedly lower at lower irrigation depths. Increasing the irrigation depth lowered the soil solution salinity, resulting in greater growth and water use, and hence leaching fractions that were nearly even over irrigation treatments, averaging 0·5. Evapo-transpiration rose in direct proportion to the irrigation depth. Potential evaporation was estimated by site pan evaporation and by the Blaney-Criddle and Penman models using climatological data; the methods agreed within 15%. The ratio of evapo-transpiration to potential evaporation increased over the growing season and approached 1·5 by pan on the highest irrigation treatment due to the combined effects of high transpiration and high evaporation from the permanently moist soil surface. The best field predictor of biomass yield was the salinity of the soil moisture in the top 15 cm of soil profile, which constitutes the root zone for this crop. Root zone salinity must be kept at 70–75 g l^{-1} for high yields. Although irrigation and drainage requirements were high compared to conventional crops, seawater irrigation appears to be feasible in medium sand and could augment crop production along coastal deserts. The possibility of using this crop for animal production is discussed.

Keywords: irrigation; halophytes; seawater; desert

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Introduction

The idea of using seawater for crop production along coastal deserts has been proposed over the past 30 years (e.g. Boyko, 1966; Epstein *et al.*, 1980; Glenn *et al.*, 1995*a*), but is not yet a practical reality. The feasibility of seawater agriculture depends first on finding salt tolerant germplasm and second on developing suitable agronomic techniques for managing highly saline water sources. Wild halophytes have the requisite salt tolerance (National Research Council, 1990) and species from several families produce high biomass or seed yields under seawater irrigation (Glenn & O'Leary, 1985; Glenn *et al.*, 1991). One of the most promising halophytes is *Salicornia bigelovii* Torr., a short, leafless, annual salt marsh plant with succulent, photosynthetic stems and flower spikes, that not only produces forage biomass but also an oilseed from which oil and protein meal can be produced (Glenn *et al.*, 1991, 1992; Swingle *et al.*, 1996).

Irrigation strategies for using highly saline water are not yet developed (Letey, 1993; Miyamoto, 1993; Miyamoto *et al.*, 1996). Field trials in which high yields were obtained with seawater used daily or twice daily flood irrigation of sand at an annual application of 18 m year^{-1} and more (Glenn & O'Leary, 1985). These high application rates are clearly impractical for farming. Several attempts have been made to scale up *S. bigelovii* production on farms of 20–250 ha using lower application rates (Clark, 1994; Glenn *et al.*, 1995*a*). They have used either flood methods to irrigate silty soil at less frequent intervals or overhead moving irrigation booms (Clark, 1994) to irrigate sandy farms at frequent intervals but shallow depths per application. The booms are modified by inserting a plastic liner so that seawater does not contact the metal surface of the boom. No insurmountable engineering problems have been reported in handling seawater and normal farm equipment is used for most tasks. However, scale-up has been hindered by water and soil management problems brought about in part by a lack of knowledge of the water requirements of halophytes grown as crops.

Miyamoto *et al.* (1996) grew several halophytes in small weighing lysimeters over a wide salinity range in the irrigation water (1·2–60 g l^{-1} seawater salts). They used a conventional irrigation strategy in which soil moisture was allowed to deplete to 50% of field capacity between irrigations and in which a 30% leaching fraction was applied. Root zone salinities rose to three times higher than salinities of irrigation water. They reported that halophytes could be grown on water up to 10 g l^{-1} following this strategy, but that seawater irrigation (30–40 g l^{-1}) would require a different strategy.

The rationale for the present assessment was based on the observation that growth of halophytes begins to decrease with salinity exceeding 10–15 g l^{-1} in soil solutions (Miyamoto *et al.*, 1996). Thus, irrigation strategies which allow substantial depletion of soil water and/or inadequate leaching may lead to unacceptable growth reductions using seawater. An alternative strategy is to use daily irrigation at irrigation quantities sufficient to maintain necessary salt leaching. Daily irrigation is feasible with the use of modern irrigation systems. However, such a strategy will lead to high evaporation losses from soil surfaces and resulting increases in salinity in the soil solution unless irrigation water is applied in excess of the potential evaporation rate. This study was conducted to evaluate biomass and seed production by *S. bigelovii* and the salinity of the soil solution in response to varying depths of daily seawater application tied to the pan evaporation rate. The crop was grown on a medium-textured sand with low water retention capacity, typical of coastal desert sands where this form of agriculture might be introduced.

Materials and methods

Buried drainage lysimeters, set into open plots of *S. bigelovii*, were used over two crop cycles. The experiments were carried out from 1994–1995 in medium sand irrigated with seawater from a well at Puerto Penasco, Sonora, Mexico, a coastal desert location. The salinity of the seawater was 40 g l^{-1}. The lysimeters were installed in the middle of a 1 ha farm divided into individually-irrigated, 200 m^2 plots, described in Glenn and colleagues (1985, 1991, 1995*a*). The farm site is set between sand dunes within 1000 m of the sea. The soil was classified as a medium sand composed primarily of quartz and feldspar subangular and subrounded grains and contained approximately 10% shell fragments and calcium carbonate (Geosciences Sedimentation Laboratory, University of Arizona). The moisture content of the sand at field capacity was low (7–8%) and the infiltration rate into the sand in the open plots was high (up to 50 cm h^{-1}).

Lysimeter boxes

The lysimeters consisted of 24, 1 m^3 boxes, embedded in the sand and equipped with drain systems to collect excess water exiting the root zone. They were installed in holes excavated in plots with boxes approximately 10 m apart (three per plot), and were lined with PVC-coated rubber liners (610 g m^{-2}, *c.* 0·2 cm thickness). The lips of the boxes were approximately 7 cm above soil level allowing the plots outside the lysimeters to be flood-irrigated. Each box was fitted with a drain tube (a 5 cm diameter PVC pipe placed in the center of the box) to convey leachate water by gravity to collection areas excavated outside the plots. The liner was reinforced with an additional layer of plastic and a PVC bulkhead fitting where the drain tube passed through the liner. The drain tube was perforated with 1 cm diameter holes near the bottom of the box and was extended 1 m above the soil surface to provide access to the drain system if it became plugged. The inserts were leak tested after the drain tubes were installed. A geotextile filter was placed around the perforated area of the drain tube to prevent sand from entering the drain tube. Sand that was excavated from the hole was mixed with a shovel then backfilled into the lysimeter box. Gaps between the boxes and the surrounding soils were backfilled with sand and plots were carefully smoothed and leveled before seeds were sown.

Irrigation treatments and leachate analyses

The 1994 experiments (the first year) used four irrigation treatments consisting of daily water applications equaling 60, 100, 140 and 180% of pan evaporation. Each treatment used three replicate boxes sown with *Salicornia* (12 boxes) with treatments randomly assigned. An additional set of 12 boxes were subjected to the same irrigation treatments but were not cropped (bare soil control boxes). The 1995 experiments used four treatments which partly overlapped but extended the upper range of the 1994 treatments; 100, 150, 200 and 250% of pan evaporation. Each treatment had four replicate boxes (16 boxes randomly assigned). Bare soil boxes were not included in 1995. For the 1995 crop all lysimeters were irrigated at 200% of pan evaporation for 5 weeks prior to sowing to equalize starting salinities and moisture content among boxes.

The daily (6 days per week) irrigation amount for each treatment was adjusted monthly based on pan evaporation data collected in earlier years using a pan located approximately 5 km from the present site by approximately the same distance from the coast (Glenn & O'Leary, 1985). At the end of each growing season the actual treatment levels were calculated based on the actual pan evaporation data. The calculated daily amount was applied in the morning using a watering can, taking care to distribute water evenly over the crop or soil surface. Peter's Complete 20-20-20 fertilizer was added to each irrigation to deliver a calculated 25 p.p.m. of nitrogen and phosphorous. Leachate from each lysimeter (drained into a covered, 50-1 capacity plastic bucket) was determined for volume and salinity weekly. The plots outside the lysimeters were also irrigated daily by flooding to provide a buffer zone.

Cropping and plant measurements

Salicornia bigelovii ripens in early fall regardless of sowing date. The 1994 crop was sown on 9 March, irrigated until 10 September and was harvested on 27 September (188 days of irrigation, 205 days total crop) whereas the 1995 crop was sown on 20 January and irrigated until harvest on 27 September (250 days). These schedules correspond to a 'short crop cycle' and a 'long crop cycle', respectively, and represent both ends of the cropping scenario (Glenn *et al.*, 1991). *Salicornia bigelovii* seeds were obtained from a commercial company, Halophyte Enterprises Inc. (Phoenix, AZ). The seeds were designated SOS-10 by the supplier; they were originally collected from a North Carolina salt marsh, then were subjected to selective breeding to produce plants with more upright stature than the parent plants. Seeds were broadcast into all experimental units at a rate of 20 g m^{-2} to ensure a dense stand of seedlings without bare spots, and at a rate of 7·5 g m^{-2} in the surrounding open plots.

Plant height was measured at intervals during the crop cycle as the maximum height of the canopy within each basin. Percent ground cover during the crop cycle was estimated from color aerial photographs taken at 2 m height above each plot. Plants were harvested by cutting them at ground level. Biomass yields were determined after drying plants in a solar-drier (35–45°C) to constant weight (approximately 4 weeks). Seeds were separated from the 1995 harvest using a hammer mill to dislodge seeds from spikes and a seed cleaner (Glenn *et al.*, 1991).

Soil sampling and salinity measurements

Soil samples were taken at approximately 8-week intervals during the cropping cycle, with the first sample taken the day before seeds were sown. A soil probe (2·5 cm diameter) was inserted into the soil at three locations and the samples were pooled to produce a single sample per lysimeter at each sampling depth. The soil was sampled near the surface (0–15 cm depth) and at 23–38 cm depth in 1994, and near the surface (0–15 cm) and two additional depths (46–61 and 79–94 cm) in 1995. Soil moisture was determined gravimetrically, and salt contents of the dried soil samples by measuring the electrical conductivity of the water extract made for 1 g soil in 50 ml distilled water. The salinity of the soil solutions was then calculated from the salinity of the extract and the soil water content with the assumption that dissolved salt concentrations decreased in proportion to dilution ratios.

Salinities of leachate samples were measured without dilution in the field using hand-held refractometers. In 1994 a Aquafauna Biomarine Refractometer (Hawthorne, CA) with a scale from 0–100 g l^{-1} was used, but some salinities exceeded the instrument range; in 1995 a refractometer with a scale from 0–160 g l^{-1} was used (Reichert Refractometer, Cambridge Instruments, Buffalo, New York). The instrument readings were approximately 20% lower than salinities determined by hydrometer or cation and anion analyses of Puerto Penasco seawater (Thompson & Glenn, 1994) and readings were not strictly linear with salinity above 40 g l^{-1}. The refractometers were calibrated over the range of each instrument using dilutions of Puerto Penasco seawater or concentrations prepared by partially evaporating the reference seawater.

Meteorological data

Daily maximum and minimum temperatures (1994–1995), precipitation, wind speed (1994 and part of 1995) and relative humidity (1994 only) were collected at a weather station on site with measurements recorded at 2 m height. The wind speed and humidity data sets did not extend through both crops due to equipment failure. Evaporation was measured using a Class A pan set on a wood pallet (1994). The pan was set within the planted area of the farm site but did not have the recommended 50 m fetch of surrounding crop in all directions since the farm site was of limited size. In 1995 a screened pan with the same dimensions and in the same location was used. For comparison with pan data, potential pan evaporation was also estimated from temperature and day length data for 1994 and 1995 using the Blaney-Criddle model for potential evapo-transpiration equals 65% of pan evaporation. (Jensen, 1973), and a modified Penman equation was used to calculate reference crop evapo-transpiration from a well-watered, full cover grass surface, using weekly 1994 wind speed, temperature and humidity data and radiation data from Yuma, Arizona (Penman, 1948; Brown, 1996).

Statistical analyses

Irrigation treatment effects were tested using a one-way ANOVA for each year's data with irrigation treatment as the categorical independent variable. If the *F* test showed that treatment effects were significant at $p < 0{\cdot}05$, means were compared using Duncan's Multiple Means Test at $p < 0{\cdot}05$. Regression analyses used individual replicate values (not treatment means) as data and were tested for significance by the *F* test. Significance level is reported as not significant (NS) at $p = 0{\cdot}05$ or significant at $p < 0{\cdot}05$ or $p < 0{\cdot}01$. Linear equations were assumed unless the ANOVA showed a significantly ($p < 0{\cdot}05$) greater fit using higher order quadratic equations. The standard error of the mean (SEM) is given in tables and figures. Experimental design and statistical tests were chosen based on Kuehl (1994).

Results

Meteorological conditions

Daily maximum temperatures were approximately 20°C at the beginning of the crop cycle but reached 35°C near the end; minimum daily temperatures ranged from 5–27°C over the crop cycle. Seasonal temperature curves were similar in 1994 and 1995 (Fig. 1(a)) but due to the earlier planting date in 1995, mean temperatures over the cycles differed slightly (24·2°C in 1994 and 22·8°C in 1995). Relative humidity ranged from 50–65% (Fig. 1(b)), typical for a coastal desert environment. Daily pan evaporation (E_{pan}) was about 15% higher in 1994 than in 1995 from March to September despite similar temperatures (Fig. 1(c)). Cumulative E_{pan} over the crop cycle was 1·58 m in 1994 and 1·68 m in 1995 (higher in 1995 due to the longer cropping cycle despite lower daily values). Wind speed ranged from 4–12 km h^{-1} (Fig. 1(d)), predominantly generated by a south-east breeze off the ocean in summer and a north-east breeze off the desert in winter. Rainfall was very low in both years: 7·5 mm over the crop cycle in 1994 and 8·5 mm in 1995.

The Blaney-Criddle and Penman models were used to check the E_{pan} estimates. The Blaney-Criddle model produced an estimate of 1·54 m potential evaporation for the 1994 crop season, close to measured E_{pan}, but the equation predicted potential evaporation of 1·90 m in 1995, 13% higher than the measured value. Screened pans are known to give lower readings than open pans by about 10% (Stanhill, 1962; Jensen, 1973). The Penman model produced a mean weekly ratio of reference crop evapo-transpiration to E_{pan} of 0·70 (S.D. = 0·09, N = 26 weeks) over the 1994 crop, which is the ratio expected for a Class A pan (Brown, 1996). The 1994 and 1995 E_{pan} data were 20% and 10% higher, respectively, than the historical data used to set irrigation rates.

Water and salt balance

Cumulative irrigation depth (W_i), evapo-transpiration (E_t), leachate depth (L_v) and leachate salinity (L_s, expressed as g l^{-1}) by irrigation treatment for 1994 and 1995 are shown in Table 1. E_t was calculated as $W_i - L_v$. In both years the target values of % E_{pan} were not achieved, as the historical data used to set the irrigation treatments were lower than measured values. W_i spanned a range from 0·73–3·79 m over the two crops. L_v increased with W_i as expected, but differences in leaching fraction (LF) among treatments were non-significant (p > 0·05), averaging 0·35 in both years. E_t, calculated by the difference between water on and water off, increased in direct proportion to W_i in both years and was the same for bare soil as for planted plots in 1994 (Fig. 2).

L_s decreased with W_i in 1994 but not 1995 (Table 1). A cumulative salt balance was calculated for the 1995 treatments (Table 2) (the 1994 salt balance could not be calculated because L_s at the end of the crop exceeded the measurement limit of the refractometer used that year). Salt loading ranged from 60–150 kg m^{-2} over the

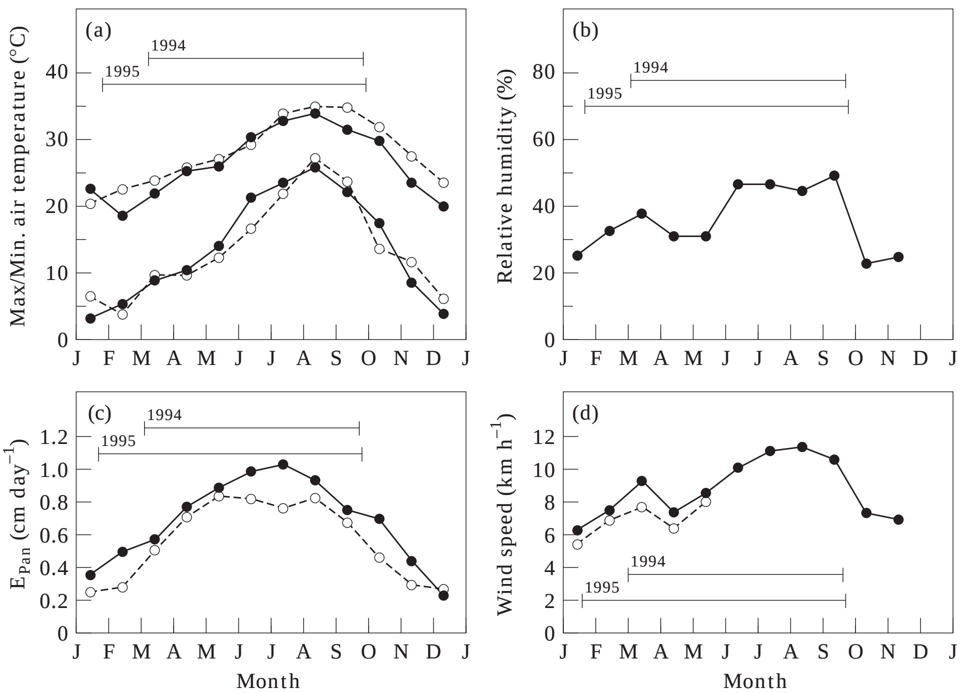

Figure 1. Weather conditions at the Puerto Penasco halophyte farm site, showing mean monthly values for daily measurements of (a) maximum and minimum temperatures, (b) relative humidity, (c) pan evaporation, and (d) wind speed. Closed circles are for 1994 and open circles are for 1995. Bars within graphs show the crop cycle in each year.

irrigation treatments. L_s increased in rough proportion to the amount added but a calculated 9–26 kg m^{-2} (9–18%) was retained in the lysimeter soil (Table 2).

In both years, constant conditions with respect to volume and salinity of leachate were not achieved; L_v decreased while L_s increased over the crop cycle and there was considerable week to week variability (Figs 3 and 4). The ratio of E_t to E_{pan} also increased during the crop cycle (Fig. 5). In 1994 E_t/E_{pan} rose from 0·5 to 1·2 over the crop cycle (mean = 1·01) when W_i was 2·37 m (150% E_{pan}) whereas in 1995 E_t/E_{pan} rose from 0·6 to 1·9 (mean = 1·46) when W_i was 3·79 m (225% E_{pan}). The temporary peak in E_t/E_{pan} in February 1995 was probably due to water building up in the lysimeters at the beginning of the season since L_v was low during the same period then increased (see Fig. 4).

Soil moisture and salinity levels

Mean soil moisture and salinity levels over each crop are shown in Table 3. Soil moisture content under daily irrigation was controlled largely by the low water retention capacity of the sand but not by the depth of irrigation. Soil moisture increased with depth; this is expected since the sand needs to become saturated before water can drain into the drainage tube. Salt content of the soil tended to decrease slightly with soil depth, but salt content expressed as salinity of the soil moisture tended to decrease more rapidly with depth. The highest soil moisture salinity was in

Table 1. *Cumulative irrigation and leachate data for lysimeters planted with* Salicornia bigelovii *and irrigated with 40 g l^{-1} seawater at Puerto Penasco in 1994 and 1995. The target irrigation treatments are compared to the achieved values based on actual pan evaporation data for each year; total irrigation volume for each treatment is also given in meters of water depth. When ANOVAs were significant, means followed by a different letter are different at* $p < 0·05$

% Pan evaporation						
Nominal	Achieved	W_i	L_v	LF	L_s	E_t
1994						
60	46	0·73	0·250a	0·34	103a	0·48a
100	81	1·28	0·482b	0·38	102a	0·80b
140	115	1·82	0·603c	0·34	95b	1·20c
180	150	2·37	0·772d	0·33	71c	1·61d
SEM			0·038	0·03	2	0·04
F			22·4	0·64	101	90·9
p			<0·01	NS	<0·01	<0·01
1995						
100	93	1·52	0·530a	0·35	105	0·98a
150	135	2·28	0·799b	0·35	95	1·47b
200	180	3·04	1·065c	0·35	100	1·98c
250	225	3·79	1·311d	0·34	100	2·46d
SEM			0·049	0·02	5	0·05
F			47·1	0·01	0·83	204·3
p			<0·01	NS	NS	<0·01

E_t = evapo-transpiration (m); L_s = leachate salinity (g l^{-1}); LF = leaching fraction; W_i = cumulative irrigation depth (m); L_v = leachate depth (m).

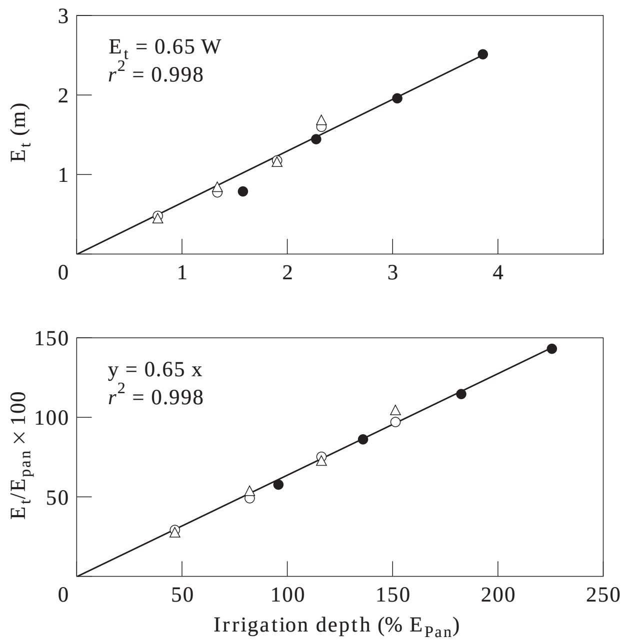

Figure 2. Relationship between irrigation depth and evapo-transpiration in lysimeter boxes planted with *S. bigelovii* (○) or left bare (△) in 1994, or planted with *S. bigelovii* in 1995 (●). The slopes of the lines were not significantly different at $p > 0{\cdot}05$. The pooled regression equations were significant at $p < 0{\cdot}01$. Error bars were smaller than symbols; SEMs across treatments were 0·04 and 0·05 m for 1994 and 1995 data, respectively.

Table 2. *Cumulative salt balance of lysimeters planted with* Salicornia bigelovii *at Puerto Penasco in 1995. Salt loaded was calculated from the volume of water added and the salinity (40 g l^{-1}); salt leached was calculated from the volume and salinity of leachate; salt stored was calculated as the difference between salt loaded and salt leached. Uptake of salt into plant tissues was less than 1 kg in all treatments and was ignored in the calculations. When ANOVAs were significant at* $p < 0{\cdot}05$ *means followed by different letters are different at* $p < 0{\cdot}05$

Treatment	Salt loaded ($kg\ m^{-2}$)	Salt leached ($kg\ m^{-2}$)	Salt stored ($kg\ m^{-2}$)
100%	60·6	51·0a	9·6a
150%	90·7	69·9b	20·8b
200%	121·7	98·8c	22·9b
250%	150·9	121·8d	29·1b
SEM		3·7	3·5
F		83·6	6·48
p		<0·01	<0·01

the 0–15 cm depth in both years. Our observations during the crop cycle and at harvest showed that the majority of roots of *S. bigelovii* were also in the top 15 cm of soil.

Soil moisture salinity in the 0–15 cm interval was the only parameter that varied significantly ($p < 0{\cdot}05$) with irrigation treatment (Table 3). Measurements tended to be variable among sampling periods (Table 4) but in general root zone salinity decreased over the crop cycle for treatments receiving 150% E_{pan} or higher, opposite

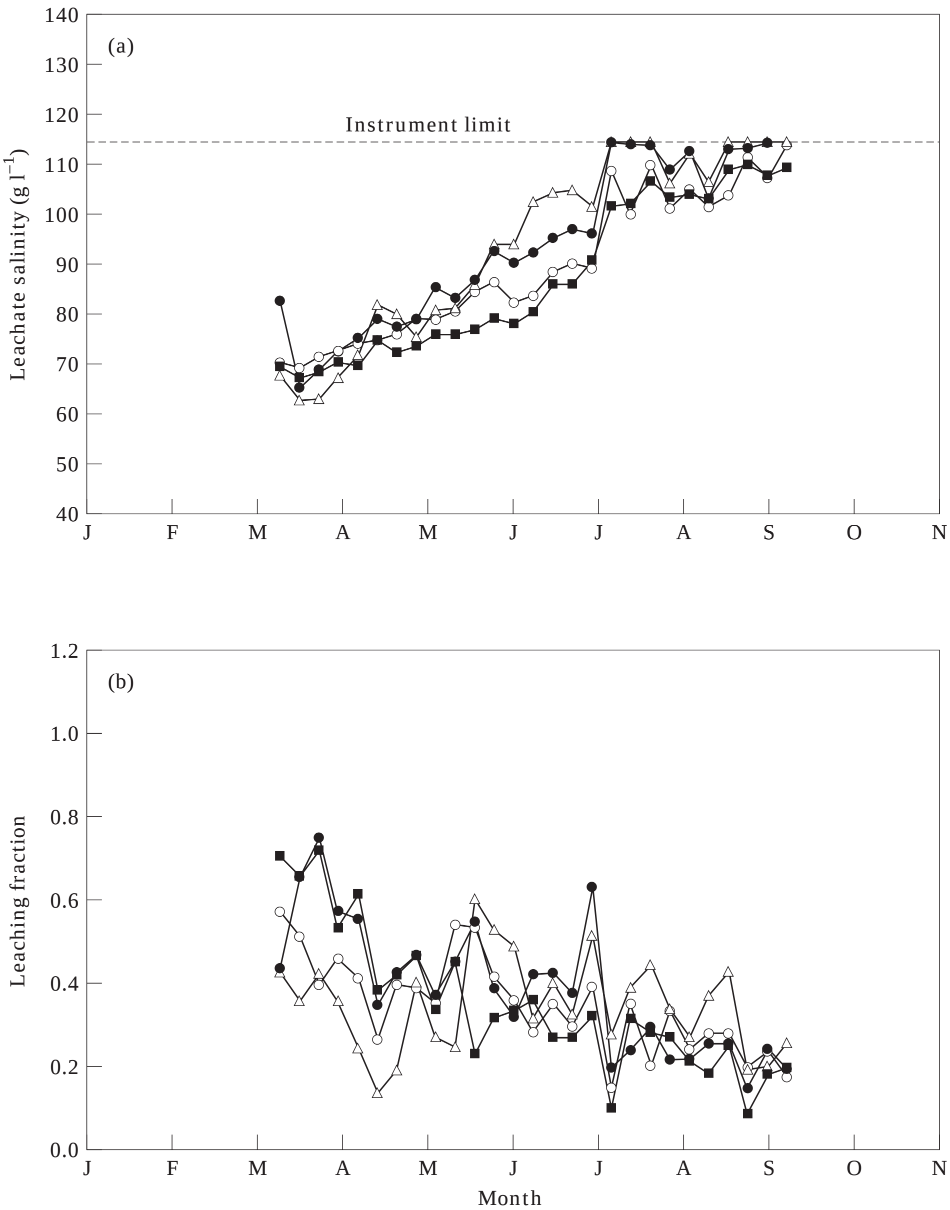

Figure 3. Changes in (a) leachate salinity and (b) leachate volume as the fraction of applied irrigation depth over the 1994 crop by irrigation treatment ((△) = 60%; (●) = 100%; (○) = 140%; (■) = 180% of E_{pan}) for lysimeters planted with *S. bigelovii* at Puerto Penasco. Data points are means of weekly measurements. Leachate salinity could not be measured above 100 g l^{-1} due to the limit of the refractometer.

to the trend noted for L_v. Hence, while the lysimeters did not reach equilibrium with respect to drainage, the salinity in the root zone did tend to stabilize over the experiments. The relationship between root zone salinity and W_i was best described by a quadratic equation in which salinity decreased with increasing W_i up to 3 m (Fig. 6).

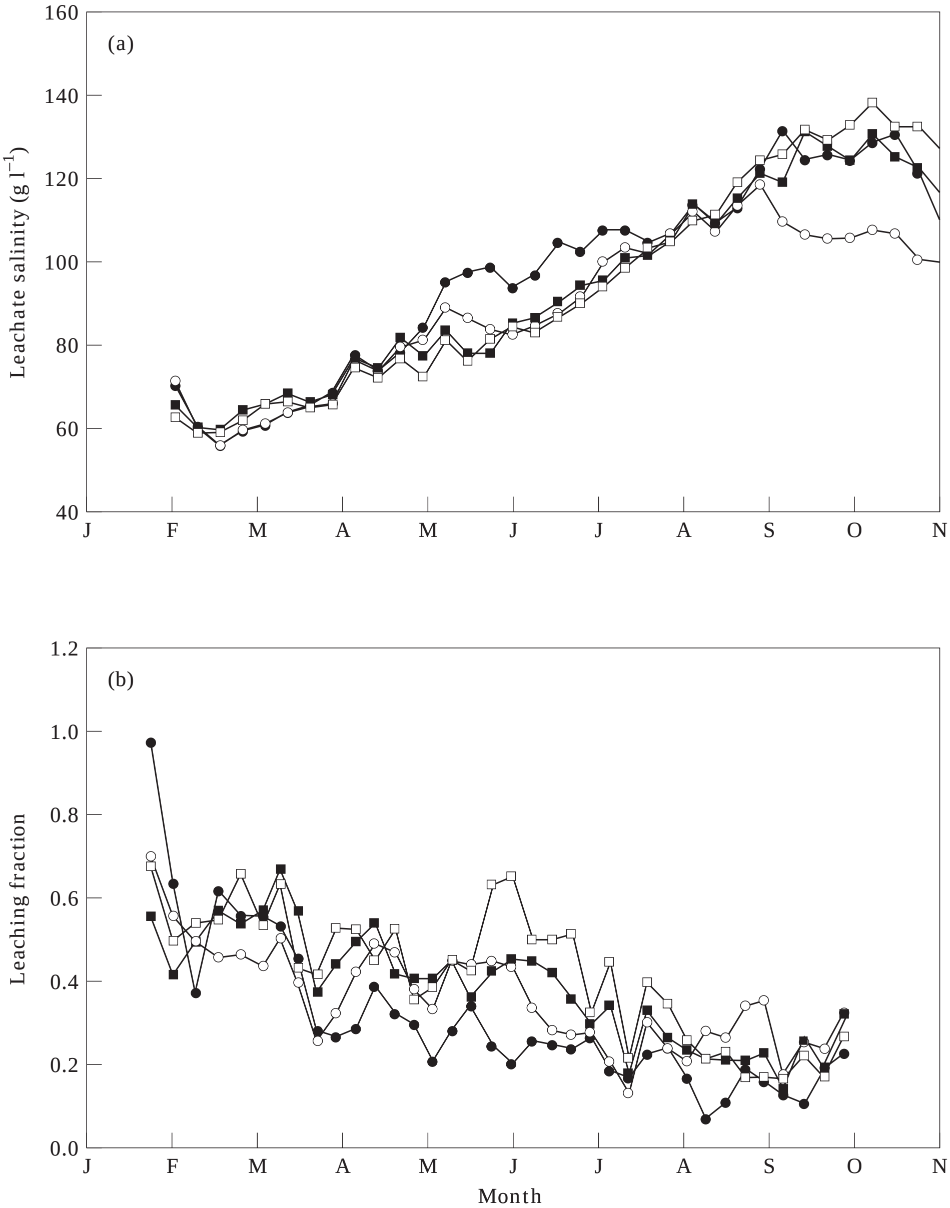

Figure 4. Changes in (a) leachate salinity and (b) leachate volume as fraction of the applied irrigation depth over the 1995 crop by irrigation treatment ((●) = 100%; (○) = 150%; (■) = 200%; (□) = 250% of E_{pan}) in lysimeters planted with *S. bigelovii* at Puerto Penasco.

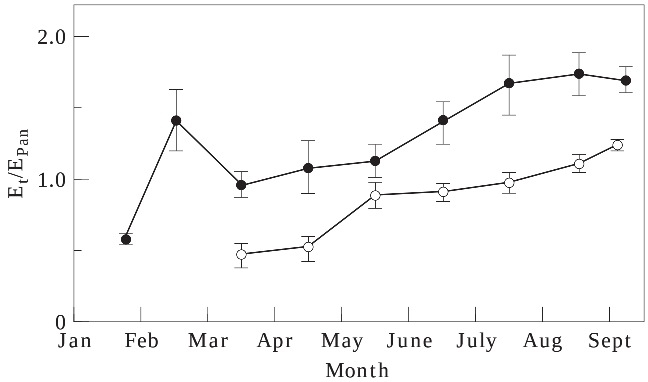

Figure 5. Ratio of E_t to E_{pan} during the 1994 (○) and 1995 (●) cropping seasons for *S. bigelovii* grown in lysimeters at Puerto Penasco. Data are for the highest irrigation treatments each year: 180% E_{pan} in 1994 and 250% E_{pan} in 1995. Bars show mean standard errors.

Growth, biomass production and seed yield under different irrigation treatments

Both plant height and percentage ground cover were positively influenced by irrigation treatment in 1994 and 1995 (Fig. 7). Plants on the 60% treatment in 1994 had only 10% ground cover at harvest and were under 12 cm high, while plants on the 100% treatments in both years produced 50% ground cover and achieved about half maximal height by harvest (maximum = *c.* 40 cm). Plants on all treatments reached their maximum height by July (flowering occurred in middle June) but continued to increase in ground cover until September through the growth of photosynthetic seed spikes from lateral buds.

Irrigation treatment had a positive effect on final biomass production (M_v) in both 1994 and 1995, whether irrigation was expressed as W_i (Fig. 8(a)) or W_i/E_{pan} (Fig. 8(b)). Coefficients of determination were above 0·9. Seed yield also increased with W_i but a curvilinear function gave the best fit to the data and individual seed weight tended to be slightly higher at an intermediate value of W_i (Fig. 9).

Water use efficiency (WUE)

WUE (kg m^{-3}) was calculated by dividing M_v by E_t (Fig. 10(a)). WUEs at similar irrigation levels were 25% higher in 1994 than 1995 but in both years, if W_i was under 2·3 m, WUE was depressed. Maximum WUEs were in the range 0·60–0·75 kg m^{-2} based on W_i (Fig. 10(a)) but when they were calculated on E_t they were much higher, 0·8–1·0 kg m^{-2}, due to the high LF associated with W_i (Fig. 10(b)).

Predicting biomass yield from root zone salinity

Although M_v was highly correlated with W_i, Tables 3 and 4 suggest that the actual constraint on biomass production must be related to an excess of soil salinity in the root zone under suboptimal W_i. Correlation matrices were calculated for 1994 and 1995 data between biomass yield and the means soil moisture and salinity parameters in Table 3. Root zone salinity was the only parameter that was significantly ($p < 0{\cdot}01$) correlated with M_v both years (r = –0·72 and –0·63 for 1994 and 1995, respectively). Regression analysis for combined 1994 and 1995 data showed the equation of best fit was linear with a moderate coefficient of determination ($r^2 = 0{\cdot}52$, $p < 0{\cdot}01$) (Fig. 11).

As root zone salinity increased, M_v decreased. When July root zone salinities (Table 4) were used in the regression analysis rather than the mean values across all sample dates, the coefficient of determination improved markedly ($r^2 = 0{\cdot}75$, $p < 0{\cdot}01$, $y = 4075 - 35x$). Hence, root zone salinity measured during the period of maximum growth and E_t was the best predictor of M_v.

Discussion

Answers to the questions of when and how much to irrigate a seawater crop are emerging from this and previous studies. On the question of when to irrigate, other experiments have already shown that sandy soil must be kept continuously moist through daily irrigation for high yields, and that dropping to an irrigation frequency of 3 days (Glenn & O'Leary, 1985) or longer (Miyamoto *et al.*, 1996) will markedly reduce yield even when large volumes of irrigation water are applied. Extending the irrigation interval results in an increase in the root zone salinity caused by soil water depletion, especially in soils with low water-holding capacity. This generalization may not apply equally to soils with greater moisture retention than sand.

Table 3. *Soil moisture (% H_2O), pore water salinity (g salt l^{-1} H_2O) and soil salt content (g salt kg^{-1} soil) at different soil depths (cm) and under different irrigation treatments (irrigation depth as % pan evaporation) in lysimeters planted with* S. bigelovii *at Puerto Penasco, Mexico in 1994 and 1995. Each value is the mean of three (1994) or four (1995) replicate boxes measured at 8-week intervals over the growing season. If the ANOVA was significant at* $p < 0{\cdot}05$, *means followed by different letters in a column are significantly different at* $p < 0{\cdot}05$

	Soil moisture		Pore water salt		Soil salt	
% E_{pan}	0–15 cm	23–38 cm	0–15 cm	23–38 cm	0–15 cm	23–38 cm
1994						
50%	7·9	6·8	107a	92	8·53	6·32
100%	8·5	7·4	93ab	83	7·93	6·08
150%	10·0	9·8	83ab	70	8·39	6·81
200%	8·7	7·5	76b	71	6·62	5·36
SEM	1·0	1·2	7	6	1·08	0·90
F	0·75	1·21	3·95	3·48	0·64	0·44
p	NS	NS	< 0·05	NS	NS	NS

	Soil moisture			Pore water salt			Soil salt		
% E_{pan}	0–15 cm	46–61 cm	79–94 cm	0–15 cm	46–61 cm	79–94 cm	0–15 cm	46–16 cm	79–94 cm
1995									
100%	7·1	7·0	15·2	91a	72	49	6·40	5·02	7·46
150%	7·9	6·5	14·4	80ab	68	51	6·28	4·38	7·09
200%	7·7	6·6	13·3	72b	61	52	5·46	4·31	6·82
250%	7·8	6·0	11·1	75b	71	55	5·78	4·23	6·02
SEM	0·9	1·1	1·25	5	4	3	0·34	0·31	0·47
F	0·93	1·07	2·00	3·63	0·74	0·71	1·65	1·40	1·72
p	NS	NS	NS	< 0·05	NS	NS	NS	NS	NS

Table 4. *Salinity of the pore water (g l^{-1}) in the 0–15 cm under different treatments depth by sampling date in 1994 and 1995 in lysimeters planted with* S. bigelovii *at Puerto Penasco. Samples were taken 24 h after an irrigation in the second or third week of the month indicated. SEM is the standard mean error*

	1994				1995			
	60%	100%	140%	180%	100%	150%	200%	250%
Jan								
Mean	–	–	–	–	83	95	81	91
SEM	–	–	–	–	6	8	10	7
Mar								
Mean	84	71	78	90	113	97	80	79
SEM	8	8	12	22	4	15	6	8
May								
Mean	111	97	116	75	89	63	59	61
SEM	13	12	19	7	19	9	3	2
July								
Mean	123	91	75	79	89	74	67	64
SEM	16	3	6	5	19	3	10	6
Sept								
Mean	110	115	64	59	81	67	65	66
SEM	5	9	4	6	13	7	5	6

The quantities of water required to grow *S. bigelovii* under daily irrigation well exceed E_{pan} and have reached 2·2 times E_{pan} or 3·8 m per season for the highest production (Table 1; Fig. 9). The high water requirement consisted of both E_t (up to 1·5 times E_{pan}) and high requirements for salt leaching (LF = 0·35). Increasing the irrigation quantity resulted in lower soil solution salinity in the root zone (a

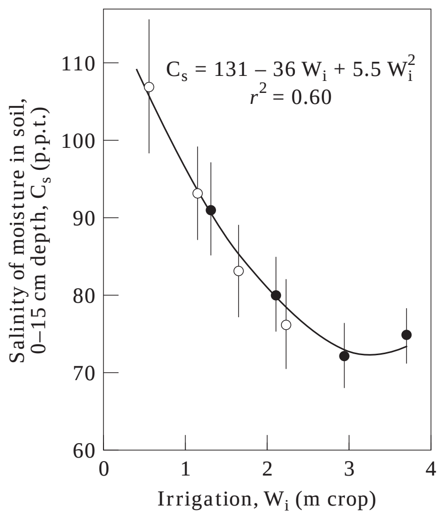

Figure 6. Salinity of soil moisture in the 0–15 cm depth in lysimeters *vs*. irrigation treatment for the 1995 crop of *S. bigelovii* planted in lysimeters at Puerto Penasco. The quadratic regression equation was significant at $p < 0·01$. Bars show mean standard errors.

determining factor of crop performance in this experiment), increased growth and water use, and thus fairly even LFs across the irrigation treatments.

The experiments showed a linear relationship between water application rate and biomass yield up to the highest rate applied. *Salicornia bigelovii* yielded 13·6–23·1 t ha^{-1} on irrigation rates of 2·3 m or above. Biomass yields and WUE based on E_t were similar to values for forage crops such as Sudan grass and alfalfa at the nearest reporting station to the experiment in Arizona (Wade *et al*., 1994). However, *S. bigelovii* required 30–40% more irrigation per unit of dry matter production, due to the high leaching fraction required when seawater is used for irrigation. Although E_t measured with gravity-drain lysimeters tend to yield higher values due to restricted drainage and advective effects, this study may serve as a guide for daily irrigation of *S. bigelovii* on sand. The irrigation quantity used here is certainly lower than the previously reported value of 18 m for a season (Glenn & O'Leary, 1985).

The components of water requirements for daily irrigation with seawater are quantitatively different from those that commonly apply to conventional crop production in three respects. First, daily irrigation results in large evaporation losses from the soil surface, as the soil is always moist. This may account for the lack of difference in E_t between the cropped and uncropped lysimeters (Fig. 2). The E_t/E_{pan} ratio approached 1·0 for bare soil under the highest irrigation treatment in 1994, indicating that first stage evaporation defined by Philip (1957) predominated despite the low water-holding capacity of medium sand. Evaporation losses could be reduced with close-spaced subsurface drip irrigation or by incorporating a mulch.

Second, E_t observed on the highest irrigation treatments exceeded E_{pan}, especially after the crop canopy developed to exceed 50% of the ground surface (Fig. 5). In

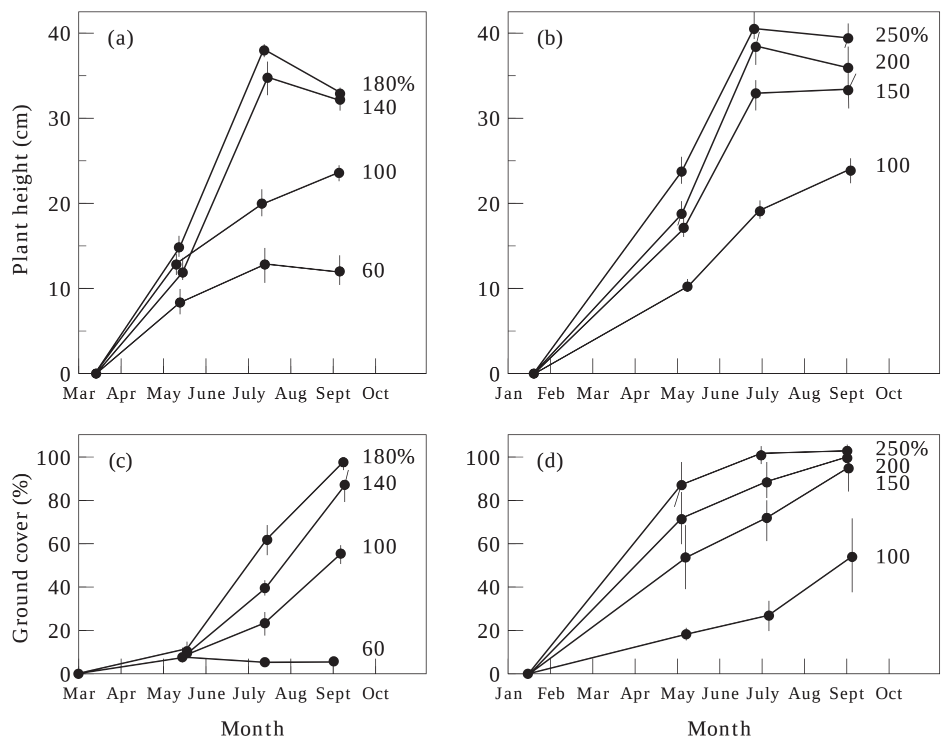

Figure 7. Growth of *S. bigelovii* plants under different irrigation treatments in lysimeters in 1994 (a,c) and 1995 (b,d) as measured by plant height and percent ground cover. Bars show mean standard errors.

conventional crop irrigation, an increase in transpiration usually results in a decrease in evaporation from the soil surface so E_t does not exceed the potential evaporation rate or E_{pan}. However, under the highest irrigation treatments *S. bigelovii* had E_t/E_{pan} ratios similar to aquatic plants in which E_t is 1·4–1·7 times E_{pan} due to the combined effects of transpiration and surface evaporation (Young & Blaney, 1942; Brezny *et al.*, 1973; Anderson & Idso, 1987; Allen *et al.*, 1992; Glenn *et al.*, 1995*b*). *Salicornia bigelovii* is a short, leafless, succulent intertidal hydrophyte with both a high transpiration rate and a relatively open canopy through which surface evaporation can take place.

Third, the quantities of water drained amounted to about 35% of the water applied during the cropping season, irrespective of irrigation treatments (Table 2). Additional water for initial salt leaching, prior to seeding, may also be required because salts tend to accumulate at the soil surface during non-cropping periods, especially under shallow water table conditions prevalent in many low-lying, coastal soils that could become available for seawater agriculture. Even though the highly salt tolerant nature

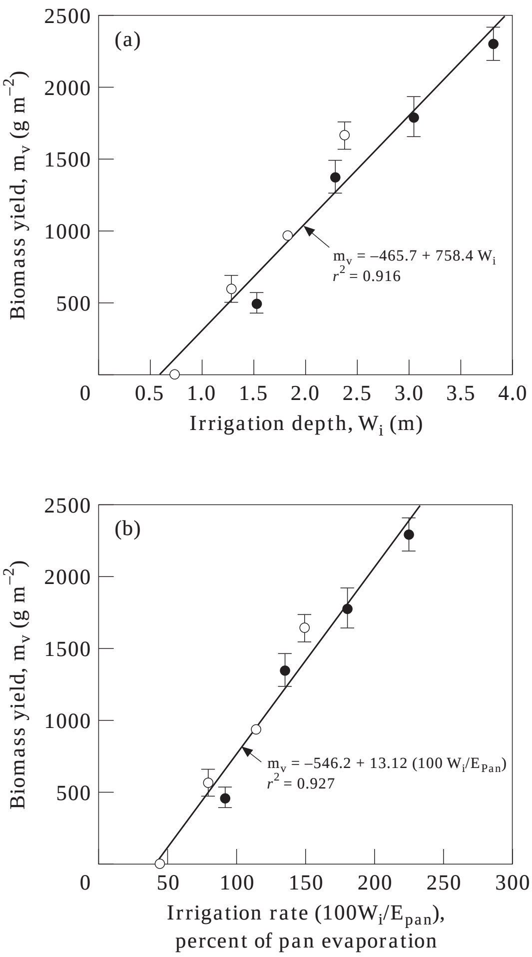

Figure 8. Linear regression of 1994 (○) and 1995 (●) biomass yield by irrigation treatments expressed as (a) total applied volume or (b) % of pan evaporation for *S. bigelovii* planted in lysimeters at Puerto Penasco. Regressions were significant at $p < 0{\cdot}01$. Bars show mean standard errors.

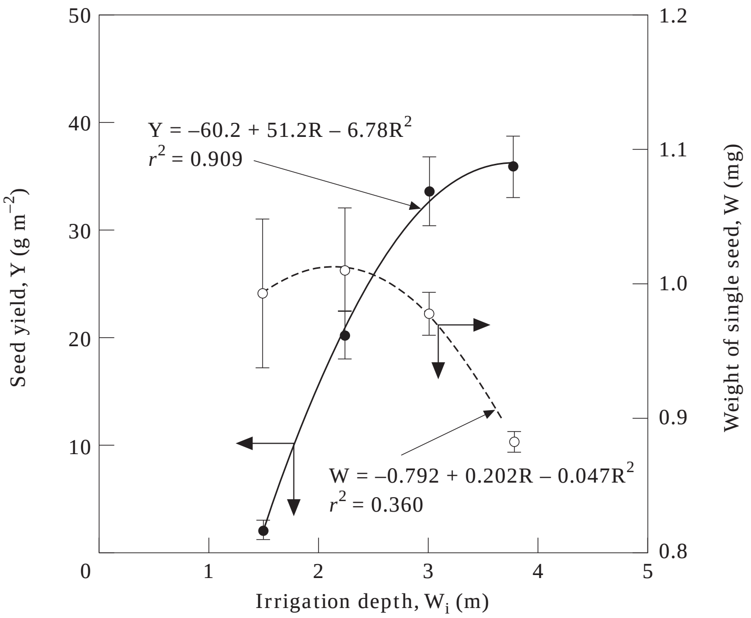

Figure 9. *Salicornia bigelovii* seed yield (●) and individual seed weight (○) in 1995 by irrigation treatment in lysimeters at Puerto Penasco. The quadratic equations were significant at $p < 0{\cdot}01$ (seed yield) or $p < 0{\cdot}05$ (seed weight). Bars show mean standard errors.

of halophytes helps reduce the leaching requirement, the quantities of water used for leaching, up to 1·33 m for the highest production, is much greater than those commonly encountered in conventional crop production.

Both water and salt balances were not at the steady state during most of the cropping seasons (Figs 3 and 4). The fact that the salt balance was not at steady state is normal in non-suction lysimeters, as salt and water must accumulate first to reach the steady state. Towards the end of the growing season, salinity of the drainage water as well as of the soil solutions in the main root zone approached somewhat stable values. The steady state salt balance equation predicts that salinity of the drainage water should approach 133 g l^{-1} at a LF of 0·30 or 160 g l^{-1} at a LF of 0·25. The measured salinity in leaching water seems to have been approaching the steady state value towards the end of the season (Figs 3 and 4).

The fact that the leaching fraction drifted to lower values within a growing season is of practical concern in managing irrigation based on E_{pan}. E_t to E_{pan} ratios increased as the crop canopy developed (Fig. 5). This pattern of water use complicates the estimate of required irrigation depth. If E_t were equal to E_{pan}, the irrigation depth which yields a leaching fraction of 0·35 would be 1·43 E_{pan} at steady state. Irrigation treatments at this rate, however, did not yield the highest biomass.

One method of adjusting irrigation depths would be to use the monthly E_t/E_{pan} ratios, a form of crop coefficient, k, obtained here. Irrigation depth would then be calculated as $(k)E_{pan}/(l–LF)$, where LF is the desired leaching fraction, which is approximately 0·35 in this experiment. One shortcoming which may result from this approach would be salt accumulation near the soil surface during low evaporation periods when E_{pan} drops as low as 0·3 cm day^{-1}. Even if a factor of 2·2 is applied to E_{pan}, irrigation depths drop to 0·7 cm day^{-1}, which does not seem sufficient to wash salts from the soil surface (Table 4 shows that root zone salinity was highest early in the season in high irrigation treatments). Early in the season it may be more efficient to irrigate every other day but with twice the depth of water application to wash salts deeper into the soil profile. This recommendation may seem to contradict the earlier statements made about the importance of daily irrigation, but not in substance when it is applied during the low E_{pan} periods when bi-daily E_{pan} is not any greater than daily E_{pan} during the major cropping period. Another problem with reliance on E_{pan} as the sole method to set irrigation schedules is the variability of pan data when site conditions cannot be strictly controlled or are not uniform over the farm site (Jensen 1973; Blad, 1983). The overall variability of estimates of potential evaporation by pan or the Blaney-Criddle model among years and at different sites along the coast is of the order of 20% in our experience at Puerto Penasco.

An alternative or supplemental method of adjusting irrigation depth may be to monitor soil solution salinity in the root zone. The method used here (determine field soil moisture then salt concentration in dilute solution) is not a standard method, but seems to be a better indicator of predicting salt effect on crop performance than soil contents per unit soil weight. This supports the idea that salt solution salinity is preferred over salinity measured in saturation extracts in appraising salinity hazards

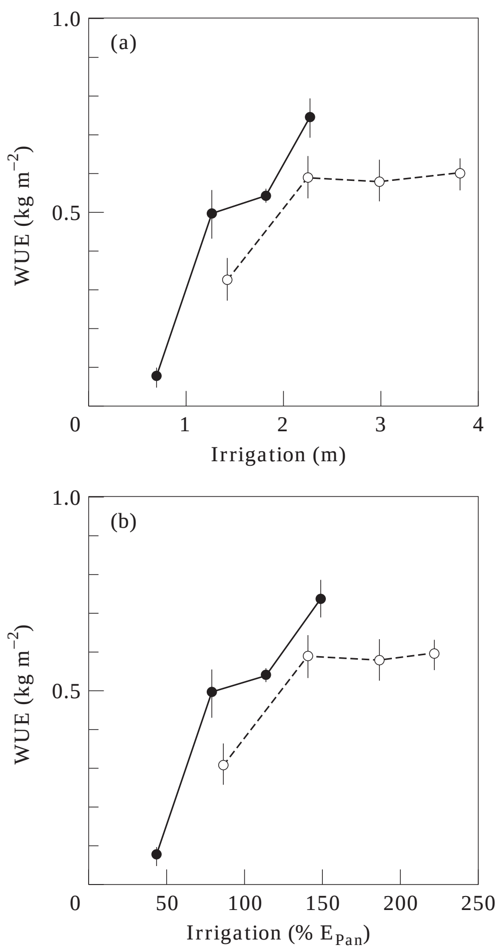

Figure 10. Water-use efficiency (WUE) of 1994 (●) and 1995 (○) *S. bigelovii* crops grown in lysimeters at Puerto Penasco. Results are presented as kg DM m^{-2} per unit of irrigation water expressed as (a) meters irrigation depth or (b) as % E_{pan}. Bars show mean standard errors.

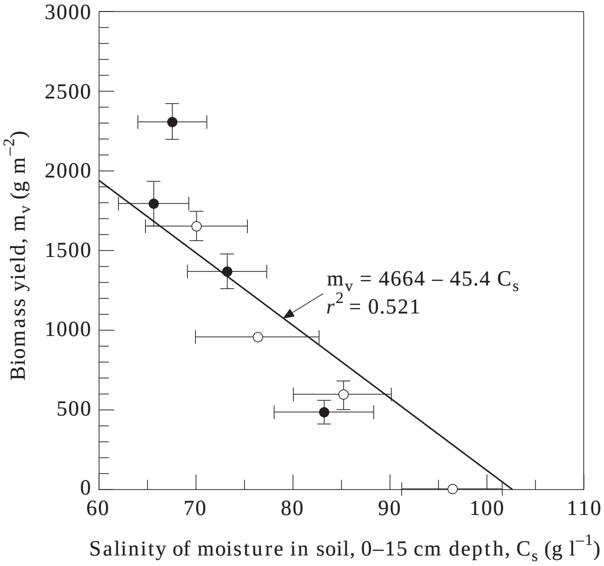

Figure 11. Regression of biomass yield on soil moisture salinity (g l^{-1}) in the top 0–15 cm of soil profile of lysimeters planted with *S. bigelovii* at Puerto Penasco in 1994 (○) and 1995 (●). The regression was significant at $p < 0{\cdot}01$.

involving irrigation with highly saline water (Miyamoto, 1993). Judging from the crop response curve (Fig. 11), salinity of the soil solution needs to be kept below about 75 g l^{-1} if high yields are to be achieved.

Another question relates to the sustainability of crop production under such an irrigation strategy. This will depend to a large extent on the permeability of the soil. Draining 1·33 m of water through sand per season is well within the hydraulic conductivity of sand near field capacity. Then, the depth of irrigation or more directly the leaching fraction will control the salt balance. This study shows that a leaching fraction of 0·35 is attainable even in a gravity-drained lysimeter. The actual leaching in sand with a deeper water table may be greater. If a leaching fraction of 0·35 is maintained through the irrigation depth adjustment discussed earlier, the salinity of the leaching water should approach a theoretical value of 114 g l^{-1}. This is approximately what was measured in the drainage water (Table 1; Figs 3 and 4). The mean salinity of the soil solution, computed as an arithmetic means of irrigation water salinity and drainage water salinity, is 77 g l^{-1}. In the high irrigation treatments the actual salinity in the root zone was close to this as a mean value over the season (Table 3) but, as mentioned, it was lower toward the end of the growing season due to the deeper leaching associated with greater irrigation depths. This is the level of salinity at which *S. bigelovii* can produce substantial biomass. If the leaching fraction is maintained at 0·35 it should be possible to control the salinity of the root zone within the desirable range indefinitely.

Seed yield also increased with W_i but not at the same linear rate. The seed yields we obtained with this variety of *S. bigelovii* were only 20% of those obtained previously using locally-collected seeds (Glenn *et al.*, 1991). SOS-10 in our experiments produced short seed spikes (3–5 cm) compared to 10–15 cm spikes produced by the native seed source (Glenn *et al.*, 1991). Short spikes were produced both years inside an outside the lysimeter boxes so the low seed yields were not due to conditions unique to the lysimeters. Biomass yields and individual seed weights of SOS-10 were comparable to previous yields obtained using the native seed source (Glenn *et al.*, 1991).

Seawater irrigation of halophytes entails paying a 'salt penalty' first in growing the crop and second in its utilization. In growing the crop, the present study shows that excess water must be used per unit biomass production to control salts in the root zone. In feeding the crop to animals raised for meat production, previous studies have shown that animals have equal weight gain and carcass quality compared to animals on conventional forage, but they have lower feed conversion and higher water intake per unit of growth due to the high salt content of halophyte forage (Glenn *et al*., 1992; Swingle *et al*., 1996). The combined salt penalty requires about 40–50% more irrigation water must be used per unit of organic matter production for seawater forage compared to conventional forage.

In many coastal desert regions there are sandy soils with sufficient hydraulic conductivity to support the high irrigation requirement, and halophyte forage crops may be feasible despite the salt penalty in areas where fresh water for irrigation is not available, or is needed for higher uses. Seawater will often require less lift than water from a deep aquifer, potentially offsetting the salt penalty. Handling drainage water is also easier near the coast than in inland situations, although questions can be raised about the impacts of elevated salinity and nutrient levels on marine or estuarine ecosystems. Overall, this study supports the potential viability of seawater agriculture by demonstrating that the very high water application rates used in previous experiments are not necessary for high yields. It also demonstrates that even though seawater is 40 times more salty than water normally used for conventional crops (Ayers & Westcot, 1976), this is offset by the high salt tolerance of halophytes. Similar experimental and analytical methods used to design irrigation and leaching strategies for conventional crops can be applied to some other halophytes on seawater, which differ from *S. bigelovii* in salt tolerance and rooting depth.

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