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Response of safflower (*Carthamus tinctorius* L.) to saline soils and irrigation I. Consumptive water use

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Abstract

Salt-tolerant crops can be grown with saline water from tile drains and shallow wells as a practical strategy to manage salts and sustain agricultural production in the San Joaquin Valley (SJV) of California. Safflower (*Carthamus tinctorius* L.) was grown in previously salinized plots that varied in average electrical conductivity (EC_e) from 1.8 to 7.2 dS m^{-1} (0–2.7 m depth) and irrigated with either high quality ($EC_i < 1$ dS m^{-1}) or saline ($EC_i = 6.7$ dS m^{-1}) water. One response of safflower to increasing root zone salinity was decreased water use and root growth. Plants in less saline plots recovered more water on average (515 mm) and at a greater depth than in more salinized plots (435 mm). With greater effective salinity, drainage increased with equivalent water application rates. Seed yield was not correlated with consumptive water use over the range of 400–580 mm. Total biomass and plant height at harvest were proportional to water use over the same range. Safflower tolerated greater levels of salinity than previously reported. Low temperatures and higher than average relative humidity in spring likely moderated the water use of safflower grown under saline conditions.

Keywords: Safflower (*Carthamus tinctorius* L.); Salinity; Saline irrigation; Water use; Root growth; Seed yield

1. Introduction

In California, disposal of saline drain water, generated in part from crop producing areas of the western San Joaquin Valley (WSJV), remains a controversial issue (Tanji, 1990, 1993). Since, closure of the region's master drain (1986), most of the WSJV has been left with no drainage outlet. Farmers have had to rely on natural drainage, or where this is

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inadequate, dispose of drain water on farm by establishing evaporation ponds (Tanji, 1990). The need to manage drainage water has led to the development of several practices intended to limit and reuse the drainage volume generated (Shalhevet, 1984; Rhoades et al., 1989; Grattan and Rhoades, 1990; Bradford and Letey, 1992; Oster, 1994; Shennan et al., 1995).

One means of decreasing the drainage volume and reduce the need for non-saline water is to irrigate crops with saline drain water (Rhoades, 1989; Grattan, 1994). Several studies have shown that moderately saline water can be used successfully to grow salt-tolerant crops without adverse long-term effects on soils (Rhoades et al., 1989; Ayars et al., 1993; Shennan et al., 1995), provided appropriate management practices are used (Shalhevet, 1984; Rhoades et al., 1989; Grattan and Rhoades, 1990; Oster, 1994). For example in the Imperial Valley, Rhoades et al. (1989) reported no yield reductions in cotton, wheat or melons. Sugarbeet response was variable. Crop quality sometimes improved with saline water application. Ayars et al. (1993) also reported no yield reductions in cotton, wheat or sugarbeets when 8.0 dS m^{-1} irrigation water was applied using a drip irrigation system, compared to those continuously irrigated with high quality water. Shennan et al. (1995) reported improved tomato fruit quality as well as sustained yields when saline water ($EC_i = 7.9$ dS m^{-1}) was applied after first flower, supplying over 65% of the crop's water requirement. That rotation consisted of 2 years of cotton before processing tomatoes, and involved reclaiming the profile with high quality water ($EC_i = 0.4$ dS m^{-1}) during cotton growth. Kaffka et al. (1999) reported no effect on sugarbeet root yield, but a reduction in gross sugar yield, at the same location.

Safflower (*Carthamus tinctorius* L.) is considered to be a moderately salt-tolerant crop (Maas, 1986) that is also exceptionally deep rooted (Weiss, 1971). Knowles (1989) observed safflower roots at 4 m or more, and studies conducted by Henderson (1981) on a Yolo loam soil in Davis, California, indicated that by maturity significant water recovery occurred at 3 to 3.6 m under favorable soil conditions. Safflower has been grown in the SJV for many years under saline conditions that restrict the growth of many other crops. Frequently in this area, safflower is grown in rotation with cotton, where it has been used to lower shallow, saline water tables resulting from the irrigation of cotton. In the Tulare Lake area of the southern SJV, the crop uses water from this saturated soil zone for a substantial portion of its growth. It is thought to lower the initial depth of perched water by as much as 1.2 m and moisture extraction below 3 m is not uncommon (Bell, 1981). Salinity in the shallow groundwater used by safflower in this region typically varies over the range of 6 to 12 dS m^{-1} and EC_e varies between 5 and 8 dS m^{-1} at 0.9–1.5 m in depth (Bell, 1981). Safflower yields under these conditions can be among the highest in the state.

While safflower has been grown for several years in the WSJV as a ‘‘moderately salt-tolerant’’ rotation crop, the use of poorer quality water and the response of safflower to varying soil and water salinities under field conditions is not well quantified. Because soil salinity may interfere with root development and water recovery at depth, the ability of safflower to extract water deep in the profile will influence both crop response to salinity, and overall farm water management. Consumptive water use under saline soils and irrigation water has not been adequately characterized. This research attempted to quantify crop growth, yield and water use of safflower when grown under different combinations of soil and irrigation water salinity.

2. Materials and methods

2.1. Site description

The response of safflower to a range of soil and water salinities was evaluated in a field experiment conducted at the University of California West Side Research and Extension Center, in the WSJV of California. Previously, the site was used for tomato–cotton rotation experiments in which varying amounts of saline drainage water ($EC_i = 7.2$–7.9 dS m^{-1}) were applied (Shennan et al., 1995), and more recently for saline drain water reuse in sugarbeets (Kaffka et al., 1999). Consequently, plots differed in residual salinity (Bassil, 2000) and provided a unique opportunity to evaluate safflower's salt-tolerance to a range of soil and irrigation water salinities at one site.

2.2. Experimental design

The soil at the experimental site is classified as a Panoche clay loam (fine-loamy, mixed, calcareous, thermic Typic Torrienthent). It is a deep, well-drained, moderately permeable with a high water holding capacity. Safflower (518S-Seedtec International) was planted on 12th March 1998 in 9.6 m $\times$ 41 m plots on raised beds 75 cm apart. Plants were drilled approximately 4.5 cm apart, which corresponded to a planting density of 292,000 plants per hectare. There was a total of 40 plots ranging in pre-plant EC_e from 1.8 to 7.2 dS m^{-1} (0–2.7 m). At the site, soil and water salinity is predominantly gypsiferous, derived from the calcareous and gypsiferous sandstone and shale parent material of the eastern slope of the Coast Range (Nielsen et al., 1973).

Prior to planting, two soil cores were collected from 20 plots from the soil surface at the top of the bed to 2.7 m deep, in 30 cm increments, using a tractor mounted Giddings rig. The plots selected reflect the range of salinity conditions observed in previous soil-salinity analyses (Kaffka et al., 1999). The samples were analyzed for EC_e using established procedures (Rhoades, 1982). A similar number and method of sample collection was used following harvest. Because salinity is a dynamic property, the salinity to which safflower was exposed and the value used for subsequent analysis was estimated to be the mean within the root zone and averaged between pre-plant and post-harvest soil sample EC_e values and referred to as effective salinity (Shalhevet, 1994).

2.3. Irrigation and water use

A soil-moisture characteristic curve was developed for the experimental site prior to the trial (data not shown). It was used to estimate the available water holding characteristics of the soils and determine the amounts of irrigation water to apply to the plots. The volumetric soil water content at field capacity (0.42 cm^3 cm^{-3}) and the permanent wilting point (0.31 cm^3 cm^{-3}) were also previously determined for this soil (Nielsen et al., 1973).

After emergence, plots were irrigated based on pre-selected treatments using either Central Valley Project (CVP) high quality canal water or saline water from a shallow well located on site. Central Valley Project water EC_i averaged 0.44 dS m^{-1} and contained less than 0.5 ppm NO_3–N and trace amounts of boron (B). Saline irrigation water EC_i averaged 6.7 dS m^{-1}, and contained 25.6 ppm NO_3–N and 5.9 ppm B. Ten plots received CVP water and the remaining 30 received saline irrigation water. Depending on water content prior to irrigation and the estimates from the soil moisture characteristic curves, each of the plots was variably irrigated until more than 500 mm of water was available (0–2.7 m) to the crop in the post irrigation period, including water derived from rainfall. During the experiment, irrigation for all 40 plots was achieved with two irrigation sets applied back to back on 24th April and 28th April. Plots were furrow irrigated and the quantity of water was monitored using a flow meter. An application uniformity near 100% was assumed (Bassil, 2000). Total irrigation water applied in all plots varied from 13 to 25 cm depending on available water at the time of application. Total rainfall during the growing period March to August was 13 cm. In California, between 510 and 630 mm of plant available water is required throughout the season to obtain economic yields near 2200 kg ha^{-1} (Kaffka and Kearney, 1998). Following the last irrigation, total water content to 2.7 m was similar among plots.

One PVC (neutron-probe) access tube was placed in the crop row in each of the twenty plots sampled for salinity. Of the 20 plots with access tubes, 6 plots received CVP water and are referred to as controls (or low salinity plots) and 14 received saline water. Out of the 14 saline plots, 7 plots had received alternating irrigation with CVP or saline water in previous sugarbeet–tomato rotations and represented moderately saline conditions (3 to 5.5 dS m^{-1}). The remaining seven plots had received only saline irrigation water plus rainfall. These are referred to as saline plots.

Volumetric soil water content (SWC), at 30 cm depth increments, was measured using a sealed-source neutron hydroprobe (CPN 503DR, Boart Longyear, Martinez California). A calibration equation for the site and instrument was developed previously (Kaffka et al., 1999). Soil water depletion (SWD) was estimated to be the difference between volumetric SWC taken between readings. Beginning 23rd April measurements were taken before and then after each irrigation, and weekly following the last irrigation (28th April) until just before harvest when no noticeable changes in volumetric SWC were detected (27th July) and plants had fully senesced. Hydroprobe estimated SWD accounted for most of the seasonal water use except approximately 46 mm that occurred before 23 April. This was estimated from locally derived ET_o and published K_c values (Allen et al., 1998). Crop evapotranspiration (ET_c) was estimated from the following water balance equation:

$$ET_c = P + I + S - D_r - R$$

where P is the precipitation (mm), I the irrigation (mm), S the change in volumetric soil water content, D_r drainage below 2.7 m, and R is the runoff. During the experiment, no significant runoff occurred. Crop coefficients for safflower grown in high and low effective salinity were determined from the equation

$$K_c = \frac{ET_c}{ET_o}$$

where K_c is the crop coefficient and ET_o is the reference crop (grass) evapotranspiration obtained from the California Irrigation Management Information System (CIMIS) weather station located at the site (Allen et al., 1998). Water use efficiency (WUE) was defined as kilogram of seed yield per millimeter of water used. Plant and canopy measurements are reported elsewhere (Bassil and Kaffka, 2001).

Seeds were allowed to dry before an area of 14 m of the center four rows of each plot was harvested on 15th August using a modified plot combine harvester. Immediately prior to plot harvests, 2 m of row were sub-sampled for biomass partitioning.

3. Results

3.1. Soil salinity

Average EC_e over the 2.7 m depth varied in different plots from 1.8 to 7.2 dS m^{-1} at planting and 1.8 to 8.1 dS m^{-1} immediately after harvest depending on each plots previous irrigation history (Fig. 1). Effective EC_e (Shalhevet, 1994), from 0 to 2.7 m, was estimated to be 2.1 dS m^{-1} for non-saline and 7.2 dS m^{-1} for saline treatments. Plots that received saline irrigation water increased in salinity by an average of 1.1 dS m^{-1}. Non-saline plots, irrigated with non-saline water, either did not change in salinity or became slightly less saline. Within saline plots, most of the salts accumulated deep in the profile, 2.25 m below the surface. In non-saline plots salinity increased with depth indicating

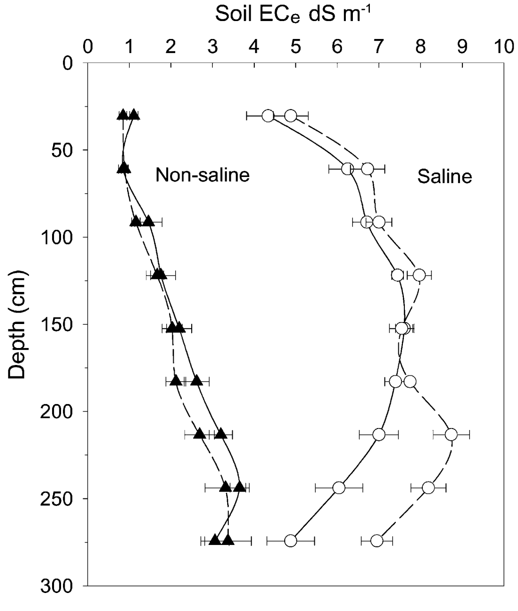

Fig. 1. Averaged pre-plant (—) and post-harvest (- - -) soil EC_e with depth (0–2.7 m) for saline (○) and non-saline (▲) plots irrigated with either saline or non-saline water. Effective EC_e at pre-plant and post-harvest is 6.5 and 7.3 dS m^{-1} and 2.2 and 2.0 dS m^{-1} for saline and non-saline plots, respectively. Error bars are S.E., $n = 7$ for saline and $n = 6$ for non-saline treatments.

good soil drainage (Fig. 1). Field observations of the saline plots confirmed a slower water infiltration rate than that noted in the non saline plots. Soil-salinity measurements are consistent with previous results (Kaffka et al., 1999) obtained at this site.

3.2. Soil water depletion

Seasonal ET_o and temperature were lower than long-term averages for the area while precipitation and relative humidity were above normal during the early part of the season (Fig. 2). Throughout most of the growing season, estimated ET_c was greater than ET_o across all plots (Fig. 3). The largest rate of daily water use occurred between 19 June and 6 July. In saline plots, daily ET_c rates were lower throughout the growing season and also began to decline sooner than in non-saline plots. Estimated consumptive water use declined by approximately 17 mm per unit increase in EC_e (millimeter of water $= -16.6(EC_e) + 556$; Bassil, 2000). ET_c between April and July averaged

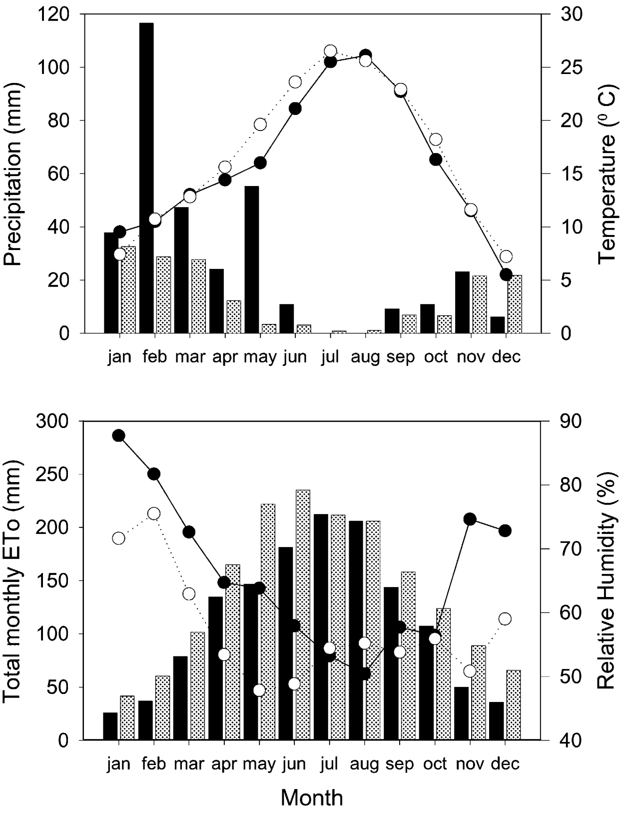

Fig. 2. Total monthly precipitation, ET_o, average temperature and relative humidity for 1998 and long-term averages obtained from CIMIS. Bars represent precipitation (upper) and total ET_o (lower). Lines are for temperature (upper) and relative humidity (lower). Black bars and solid lines represent 1998 data. Shaded bars and broken lines represent long-term averages.

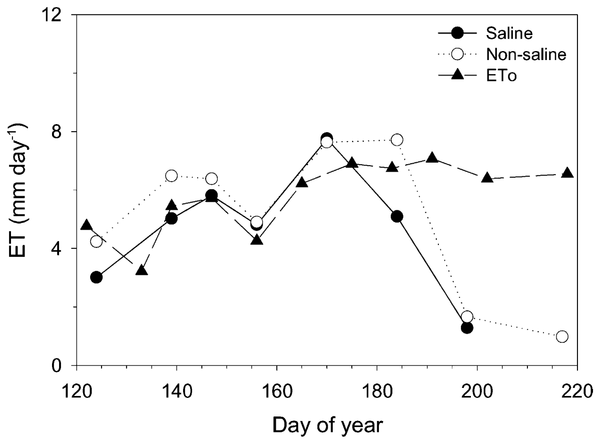

Fig. 3. Reference (ET_o) and crop (ET_c) evapotranspiration of safflower grown in non-saline ($EC_e = 2.1$ dS m^{-1}) and saline ($EC_e = 7.2$ dS m^{-1}) soil. ET_o is derived from a CIMIS weather station located at the experimental site. ET_c was calculated from soil water depletion measured using a sealed-source neutron hydroprobe.

515 mm (18 mm S.E.) in non-saline plots and 435 mm (9 mm S.E.) in saline plots (Figs. 3 and 4), significantly less. On average, plants grown in plots with low EC_e recovered approximately 100 mm more water below 1.5 m than plants grown in saline plots (Fig. 4).

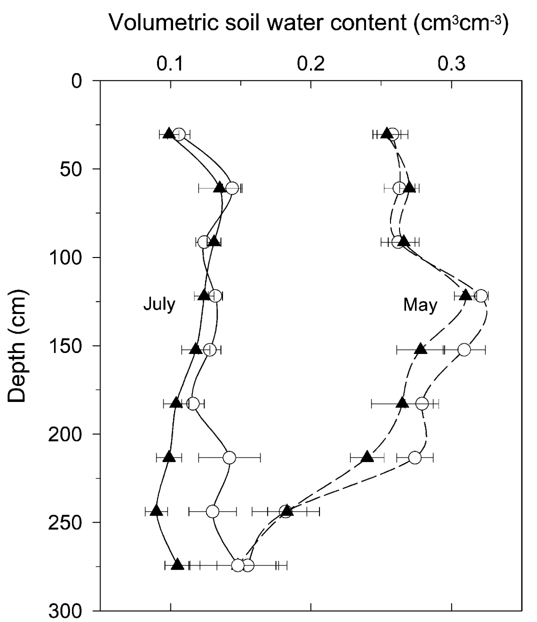

Fig. 4. Volumetric soil water content with depth (0–2.7 m) in differentially salinized plots measured at two dates (4 May (- - -) and 14 July (—)). Average effective EC_e was 7.1 dS m^{-1} (○) and 2.1 dS m^{-1} (▲). Error bars are S.E., $n = 6$ and $n = 7$ for non-saline and saline plots, respectively.

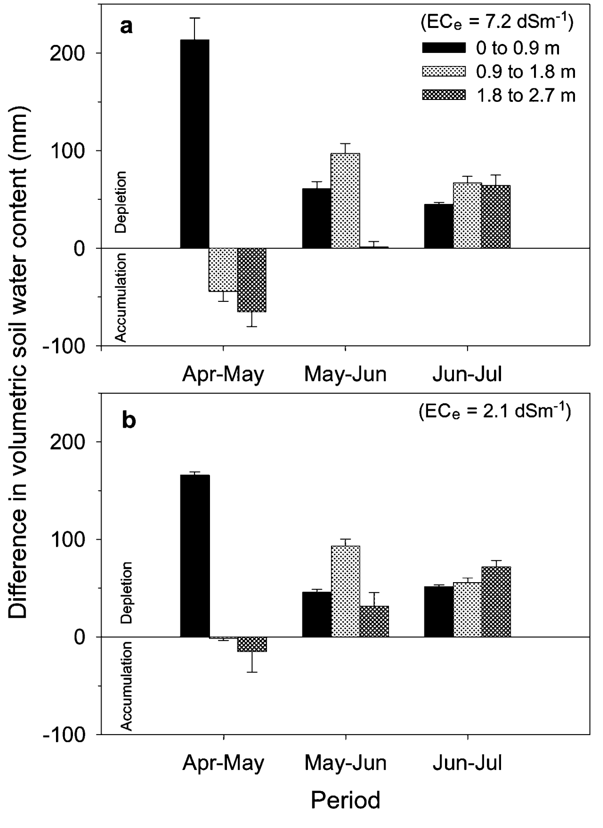

Fig. 5. Differences in volumetric soil water content (during indicated period) by depth in saline ($EC_e = 7.2$ dS m^{-1}) and non-saline ($EC_e = 2.1$ dS m^{-1}) soil during safflower growth. Negative and positive values indicate soil water accumulation and depletion, respectively. Error bars are S.E., $n = 7$ and $n = 6$ for saline and non-saline plots, respectively.

3.2.1. Drainage

Estimating ET_c based on SWD does not allow for easy separation of drainage from ET_c, especially early in the season when ET_c is small and irrigation is occurring. During irrigation and approximately 2 weeks following the last irrigation, water moved downward in the profile creating non-equilibrium conditions (April–May, Fig. 5). Between April and May in the top 0.9 m of the profile, SWD (represented by positive values) occurred and was greater under conditions of high effective salinity (Fig. 5). Below 0.9 m, SWC increased at the end of the April–May period in both saline and non-saline plots, but this was significantly greater in saline plots (Fig. 5). For an increase in SWC to occur in saline plots, the net downward movement of water had to be greater than measurable ET_c for the period. This suggests that drainage occurred under high effective salinity. In non-salinized plots, ET_c was probably much greater than any drainage, otherwise, the difference observed in volumetric SWC between April and May would have been much larger.

Regardless of the confounding of drainage with ET_c during this period, cumulative seasonal consumptive water use was not affected by the small amounts of water associated with measurement uncertainty. No change in SWC was detected below 2.5 m after the last irrigation (Fig. 4). Over the entire season, moisture depletion below 2.7 m likely did not occur in saline plots, but may have occurred in non-saline plots (Fig. 4). Following the post irrigation period, steady-state conditions reached the upper profile, and some drainage and ET_c estimations were possible.

Moisture depletion by depth was affected by crop development and climate as well as by effective salinity. Early in the growing season, most water use occurred in the top 0.9 m of the profile while at the end of the season most water use occurred below 1.8 m. Soil water depletion occurred deeper in the profile as the season progressed (Fig. 5). This trend of seasonal water use by depth was similar among plots despite the level of salinity. Furthermore, less water use occurred below 1.8 m in saline plots between May and June and between June and July than in non-saline plots. Fig. 6 quantifies relative and absolute SWD by depth over the entire season.

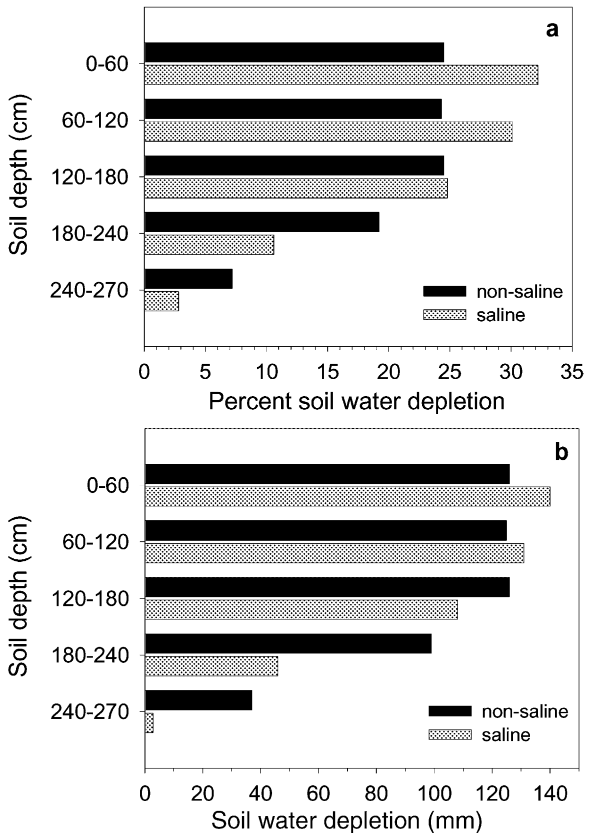

Fig. 6. Relative (a), and absolute (b) soil water depletion by depth over the entire safflower growing season in saline and non-saline conditions. Effective salinity of saline plots ($n = 7$) averaged 7.2 dS m^{-1} and that of non-saline plots ($n = 6$) averaged 2.1 dS m^{-1}.

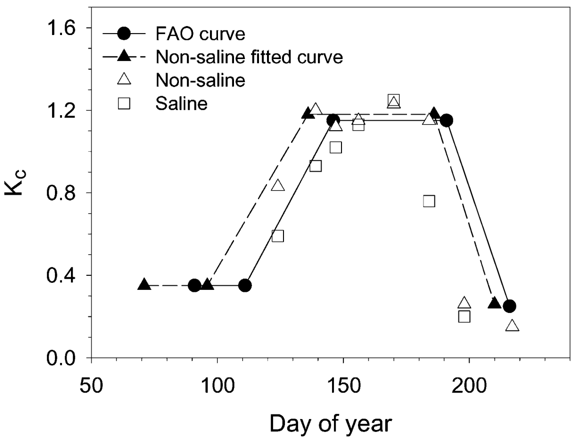

Fig. 7. Crop coefficients (K_c) developed for safflower grown in saline ($EC_e = 7.2$ dS m^{-1}) and non-saline ($EC_e = 2.1$ dS m^{-1}) conditions. FAO curve constructed using data derived from Allen et al. (1998). The non-saline curve was drawn using K_c values from this experiment and growth stage data from Allen et al. (1998). Growth stages were modified slightly to represent safflower growth typical for the SJV. A curve for saline grown safflower was not developed because of uncertainties in dates of growth stages.

3.2.2. *Crop coefficients*

Differences in consumptive water use across the range in effective salinity as well as subsequent effects of salinity on plant growth and development led to differences in K_c estimates. K_c for both saline and non-saline plots were determined from estimated ET_c and meteorologically derived ET_o values (Allen et al., 1998) and used to construct a K_c curve based on average values for a given period (Fig. 7). Under non-saline conditions, K_c estimates fall within the range of previously published values (Allen et al., 1998) except that in California, safflower develops over a longer growing season (Kaffka and Kearney, 1998) than that reported by Allen et al. (1998). The K_c curve derived from data collected in this experiment shows more rapid canopy development, and maximum K_c values were attained earlier than predicted by Allen et al. (1998) (Fig. 7). The K_c for safflower grown in saline plots reached maximum values later at mid-season and declined sooner, at season's end. This is consistent with earlier crop maturity observed for safflower grown in saline plots. Full bloom occurred near 26th June for safflower in saline plots and near 7th July for safflower in non-saline plots (Bassil and Kaffka, 2001).

3.2.3. *Plant response*

Seed yield was not correlated with consumptive water use over the range of 400 to 580 mm (Fig. 8). However, total biomass and the height of sub-samples at harvest were directly proportional to water use (April–July) over the EC_e range 2.1–7.2 dS m^{-1} (Fig. 9). Both biomass and height increased with increasing amounts of water used, as expected. Height increased by 0.22 cm mm^{-1}. The biomass regression line (Fig. 9) does not pass near the origin (y intercept is -970) because the figure does not represent cumulative seasonal biomass, and instead represents the total final biomass

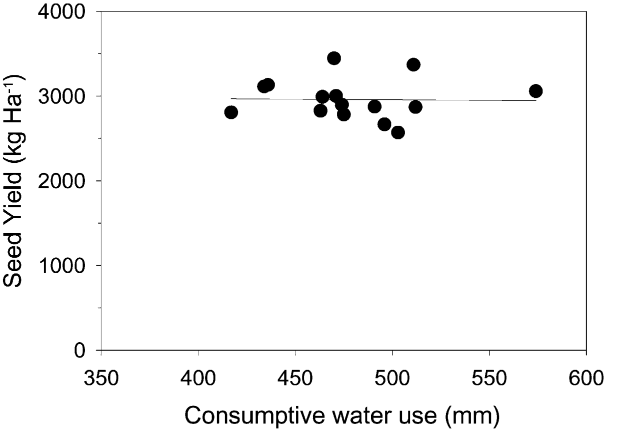

Fig. 8. Seed yield and consumptive water use of safflower grown in soils having a salinity gradient ranging in effective EC_e from 2.1 to 7.2 dS m^{-1}. Water use was estimated from changes in soil water depletion measured using a sealed-source neutron hydroprobe. Data points represent individual plots.

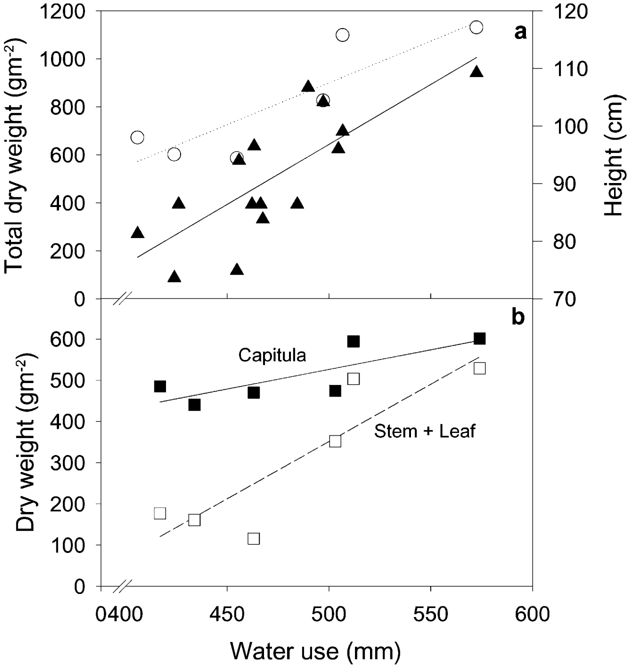

Fig. 9. (a) Sub-sample total dry weight (○, - - -), maximum height (▲, —); and (b) sub-sample biomass components (capitula, ■, —; stem plus leaf, □, - - -) as a function of consumptive water use of safflower grown in soils having a salinity gradient. Effective EC_e ranged from 2.1 to 7.2 dS m^{-1}. Water use was estimated from volumetric soil water content measured using a sealed-source neutron hydroprobe. Sub-sample area harvested (by hand) was 2 m of one row. Data points are individual plots. Regression equations are as follows: total dry weight $= 3.7x - 969$ ($r^2 = 0.76$); height $= 0.22x - 15$ ($r^2 = 0.60$); capitula weight $= 0.95x + 50$ ($r^2 = 0.63$); stem and leaf weight $= 2.78x - 1038$ ($r^2 = 0.78$), where x is the water use (mm).

and water use of plots that differ in salinity stress. Capitula biomass (seed head) was less well correlated with water use than stem plus leaf biomass (Fig. 9). Stem plus leaf biomass increased at 2.78 g m^{-2} mm^{-1} water. Capitula biomass increase was 0.95 g m^{-2} mm^{-1} water, and was only 34% of the stem plus leaf weight increase. Water use efficiency was estimated for the same plots represented in Fig. 8. Water use efficiency was nearly 1 kg seed per millimeter of water used greater in the saline plots (Bassil and Kaffka, 2001).

4. Discussion

4.1. Consumptive water use

Cooler weather and high relative humidity during the early part of the season (Fig. 2) probably reduced transpiration and likely moderated the effects of salinity on crop growth and correlated water use. High temperature tends to lower the crop's threshold for salinity stress either because of increased transpiration or changes in leaf biochemistry (Shalhevet, 1994). With higher atmospheric humidity, the effect of the salt stress also can be moderated. It is possible that higher relative humidity can increase salt-tolerance in salt-sensitive plants such as bean more than in tolerant ones such as cotton (Hoffman and Rawlins, 1970, 1971; Hoffman et al., 1971).

Estimated SWD accounted for most of the seasonal consumptive water use. Any water use that may have occurred prior to SWD measurements was probably similar between saline and non-saline treatments, small in amount, and therefore did not bias results significantly. During irrigation and the 2 week period following the last irrigation, drainage losses in saline plots could not be distinguished from water use in the upper third of the profile (Fig. 5) based on the water balance equation. No instruments were in place to measure the flow of water in the profile independent of ET_c, or to measure safflower water use directly rather than from SWD.

In saline plots, more drainage may have occurred because plant growth was reduced by the end of May (Fig. 5). Pang and Letey (1998) have suggested that increasing soil or water salinity reduces transpiration and increases drainage for a given irrigation volume. By the end of May, canopy height and plant biomass were reduced in saline plots (Fig. 9), compared to non-saline plots, consistent with estimated drainage patterns observed in this trial and Pang and Letey's theory.

Based on the water balance equation, consumptive water use declined at higher EC_e and increased at depth with time. In non-saline plots, more water use occurred later in the season and deeper in the profile compared to saline plots. With increasing salinity, SWD from the lower third of the profile decreased more than in the top third (Fig. 6).

One response of safflower to increasing root zone salinity is decreased water use and root growth. The data for water use, N-depletion (see Bassil and Kaffka, 2001), and EC_e by depth all suggest that safflower roots in saline plots were not active deeper than 2 m. Earlier physiological maturity could have accounted for some of the observed reduction in rooting depth of safflower grown in saline plots (Bassil and Kaffka, 2001).

4.2. Plant response

Total plant biomass was highly correlated with water use over the range in EC_e described. Capitula weight changed less than stem and leaf weight because it is correlated more closely to seed yield. Seed yield was not correlated with water use. Furthermore, WUE of safflower grown in saline and non-saline conditions averaged 6.46 and 5.49 kg seed per millimeter respectively (Bassil and Kaffka, 2001). These data are consistent with the observed increase in harvest index, resulting from reduced amounts of stem plus leaf biomass compared to capitula in saline plots. Although, root zone salinity reduced the effective water available to the crop, decreased water use did not adversely affect crop yield (Fig. 8). Safflower's evaporative demand was correlated with reduced height and leaf area in saline plots. Safflower plants responded to water limitations in saline plots by adjusting crop development rate, plant size, and harvest index.

Few crop coefficient values have been reported for safflower. The only published data are reported by Allen et al. (1998) and references therein. The development of a K_c curve for safflower grown under saline conditions is the first attempt to estimate K_c under stressed conditions (Fig. 7). The K_c curve for stressed safflower is in agreement with other data collected in this experiment, namely earlier maturation and a smaller crop canopy.

5. Conclusions

Safflower root growth and water use at depth was restricted in salt-affected soil. Increasing salinity reduced safflower biomass, daily and cumulative seasonal ETc. Reducing water use increased drainage in salt-affected plots for the same irrigation volume. Despite these effects, safflower seed yield was not significantly influenced by soil or irrigation water salinity. Saline water can be used to irrigate safflower without yield loss if the effective salinity levels of soil and water are less than 8 dS m^{-1}, in a carefully managed cyclic reuse program.

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