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Response of safflower (*Carthamus tinctorius* L.) to saline soils and irrigation II. Crop response to salinity

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Abstract

Safflower was grown in previously salinized plots that varied in effective 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. Differences in pre-dawn and mid-day plant water potential, between saline and non-saline treatments, were significant at several dates. Leaf area index (LAI) declined by one unit over this salinity range. Plant populations were not affected, however, plant height was reduced by 32 cm between saline and non-saline plots. Seed and oil yield were not affected by increasing EC_e, but oil content and 1000 seed weight increased slightly. Harvest index increased with salt stress due to a reduction in the ratio of stem to total biomass. Bud weight per m^2 was less affected by salinity. Safflower tolerated greater levels of salinity than previously reported. Below average temperatures and higher than average relative humidity in spring likely moderated the effects of salinity. Safflower is a viable alternative for use in rotations where saline soils and irrigation water limit production of non-tolerant crops.

Keywords: Safflower (*Carthamus tinctorius* L.); Salinity; Drainage water; Seed yield; Oil; Biomass partitioning; Leaf area

1. Introduction

Irrigated systems cannot continue to be productive without maintaining a salt balance within the soil profile that is conducive to crop production (Tanji, 1990; van Schilfgaarde, 1990; Shalhevet, 1994). Limitations to drainage can lead to a shift in the crops grown

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(Rhoades et al., 1989). This has occurred in the western San Joaquin Valley (SJV) where increases in soil salinity are occurring because hydrogeochemical constraints exist and off-site drainage disposal options are limited by regulation (Tanji, 1990, 1993). The types of crops grown determine the relative salinity of the soil profile that can be tolerated (Shalhevet, 1994) and the amount of saline drainage water that can be used for irrigation (Oster, 1994). In parts of California's western SJV where salinity cannot always be kept within levels acceptable to sensitive crops, salt tolerant crops will become increasingly important in crop rotations (Grattan, 1994; Pasternak and De Malach, 1994).

Safflower (*Carthamus tinctorius* L.) is considered to be a moderately salt-tolerate crop (Maas, 1986) and has been grown in the SJV for many years in conditions where salts restrict the growth of many other crops (Kaffka and Kearney, 1998). While generally regarded as tolerant, safflower yields also have been reduced by high levels of soil salts (Francois and Bernstein, 1964; Francois et al., 1964; Yermanos et al., 1964; Rains et al., 1987; Irving et al., 1988; Beke and Volkmar, 1995). The use of saline water on safflower has diverse effects. It is reported to be more sensitive to salinity at germination than at later growth stages, because salinity reduces the rate and percent emergence at levels lower than those affecting plant growth (Francois and Bernstein, 1964; Francois et al., 1964; Yermanos et al., 1964; Ghorashy et al., 1972). Typically, salt-affected safflower plants are smaller, more succulent with thickened and darker green leaves (Weiss, 1971). Stem diameter and plant height also are reported to decrease with increasing salinity (Francois and Bernstein, 1964; Kurian and Iyengar, 1972). Transpiration rates are lowered, leaf cell structure is altered, and stomatal numbers are reduced (Weiss, 1971). Flowering and maturity can be hastened (Francois and Bernstein, 1964; Devi et al., 1980). The number of capitula (flower heads) per plant and seed number per capitula may be reduced, particularly in tertiary heads (Francois and Bernstein, 1964; Yermanos et al., 1964; Irving et al., 1988). The reduction in the number of capitula per plant appears to be greater than the reduction in seed number per capitula (especially, in primary capitula) because seed yield per capitula is not as readily affected. Seed oil content also has been reported to decrease with increasing salinity (Francois et al., 1964; Yermanos et al., 1964; Beke and Volkmar, 1995). Sometimes, intermediate levels of salinity (Francois and Bernstein, 1964; Rains et al., 1987) as well as small amounts of sodium (Aslam, 1975; Devi et al., 1980) appear to increase yield by favorably affecting harvest index. Genotypic variation to salinity tolerance has also been reported (Knowles, 1989). Other factors that affect safflower's tolerance to salinity include climate, weather, irrigation, soil conditions and fertility (Robbelen et al., 1989; Kaffka and Kearney, 1998).

Safflower is one of a few crops well suited to the cropping systems of the western SJV's salt-affected soils. Most studies relevant to the SJV were carried out several decades ago (Kaffka and Kearney, 1998), and while they are generally still valid, new tests within the SJV would be valuable, particularly under salt-affected conditions. Here, we present results on the effects of saline conditions on safflower biomass, yield and yield components. Safflower water use under saline conditions is reported in part I (Bassil and Kaffka, 2001).

2. Materials and methods

2.1. Experimental design

Experimental conditions were reported previously by Bassil and Kaffka (2001). Briefly, the site contained a total of 40 plots ranging in pre-plant EC_e from 1.8 to 7.2 dS m^{-1} (0–2.75 m). Prior to planting, two soil cores were collected from 20 plots from the planting row, in 30 cm increments (0–2.7 m deep). Soil samples were analyzed for EC_e by the method of Rhoades (1982) and for NO_3–N (Keeney and Nelson, 1982). A similar number and method of sample collection was used following harvest. Safflower (518S-Seedtec International) was planted on 12th March 1997 in 9.6 m × 41 m plots on raised beds 75 cm apart. Plots were irrigated based on pre-selected treatments using either Central Valley Project (CVP) canal water ($EC_i = 0.44$ dS m^{-1}; NO_3–N = 1 ppm) or saline water ($EC_i = 6.7$ dS m^{-1}; NO_3–N = 26 ppm) from a shallow well located on site. The effective salinity to which safflower was exposed (following Shalhevet, 1994), was estimated to be the mean between pre-plant and post-harvest soil samples averaged within the root zone (2.7 m).

2.2. Plant and canopy measurements

Crop growth was monitored in saline, moderately saline and non-saline plots (effective $EC_e = 6.8$, 3.1 and 1.6 dS m^{-1}, respectively) by collecting plant samples and measuring plant height throughout the growing season. Days to 50% and 90% full bloom were estimated visually. Leaf area index (LAI) was estimated once using a laser-induced chlorophyll fluorescence meter (Denison and Russotti, 1997) on 22nd May, when plants reached a maximum leaf area. Pre-dawn (Ψ_{pre}) and mid-day (Ψ_{mid}) leaf water potentials were determined with a pressure chamber using N_2 gas (Hsiao, 1990). The primary capitula and part of the stem containing at least two fully expanded leaves was used. Readings were taken on 23rd June, 29th June and 6th July from one saline and one non-saline plot. Seeds were allowed to dry in order to reach approximately 8% moisture. An area of 14 m long 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 yield components and carbon partitioning determinations, including: plant number, bud, stem and seed weights, and primary to quaternary bud development. Oil content was analyzed using NMR techniques (Gambhir, 1994).

2.3. Nitrogen management

Because the saline irrigation water also contained 26 mg kg^{-1} NO_3–N, plots differed in residual NO_3–N as a function of the amount of saline irrigation water applied in prior years (Shennan et al., 1995; Kaffka et al., 1999). Average values in saturation extracts ranged from 40 to 151 ppm NO_3 (0–2.7 m). In order to minimize any possible confounding effects of variability in initial residual soil N with salinity treatments, non-saline plots were differentially fertilized by applying liquid calcium ammonium nitrate fertilizer (CAN 17) with an early season irrigation (Burt et al., 1995). Nitrogen was added

to supply 150 kg N ha^{-1}, from all sources, to the top 1.2 m of the soil profile of each plot. Only the top 1.2 m of the profile was considered because it was not feasible to equalize NO_3 throughout the whole profile among all plots. Nitrogen application rates were estimated using the following equation:

$$N_{rsd} + N_{irr} + N_{min} + N_{CAN} = 150\,kg\,N\,ha^{-1}$$

where N_{rsd} is the residual soil N determined prior the experiment (0–1.2 m), N_{irr} the amount of NO_3 in the water to be added with the remaining irrigation, N_{min} the soil mineralizeable N estimated using 5% N in 0.7% organic matter mineralizing at 0.7% per year in conditions with adequate moisture and temperature over the growing period (Stanford and Smith, 1972), and N_{CAN} is N to be added as CAN fertilizer. A rate of 150 kg N ha^{-1} is considered sufficient for maximum yields under a range of conditions in California (Kaffka and Kearney, 1998). Total leaf N content was analyzed by total N combustion (Leco FP-528) from safflower leaf samples collected on 23rd June and 6th July. The dates correspond to just before and immediately following full bloom for both saline and non-saline plots. A description of profile salinity in saline and non-saline plots is reported elsewhere (Bassil and Kaffka, 2001).

3. Results

3.1. Plant response

Full bloom occurred near 26th June for safflower in saline plots and near 7th July for safflower in control plots. Pressure chamber readings conducted at pre-dawn and mid-day resulted in differences between saline and non-saline plots at several dates (Table 1). Over

Table 1
Safflower water potential (Ψ) near full bloom in high and low salinity plots

Ψ[a]	EC_e (dS m^{-1})[b]	
	1.96	7.18
6/23/1998 (MPa)		
Pre-dawn	−0.74 (0.07)[c]	−1.06 (0.08)
Mid-day	−2.19 (0.04)	−2.69 (0.01)
6/29/1998 (MPa)		
Pre-dawn	−1.08 (0.04)	−2.04 (0.05)
Mid-day	−2.10 (0.08)	−3.05 (0.09)
7/6/1998 (MPa)		
Pre-dawn	−1.70 (0.07)	−2.95 (0.10)
Mid-day	NA[d]	NA

[a] Readings taken from primary flower branch and included two fully expanded leaves.
[b] Effective salinity determined as the average of two cores per plot of nine, 30 cm samples to 2.7 m.
[c] Numbers in parenthesis are standard errors; $n = 3$.
[d] Reading exceeded pressure chamber range of 4 MPa.

this range of effective salinity, pre-dawn water potential differences increased sequentially from approximately 0.32 to 0.96 to 1.25 MPa between 23rd June and 6th July. Mid-day water potential differences were 0.5 and 0.95 MPa between 23rd June and 29th June, respectively. Because of differences in crop development rate, water potential values can be compared at similar developmental stages by comparing successive dates, between plants in non-saline plots on 29th June and plants in saline plots on 23rd June, and between those in non-saline plots on 6th July and those in saline plots on 29th June. The comparison of plants at similar developmental stages (between the two levels of salinity) also reveals sequentially higher differences of water potential over time for both pre-dawn and mid-day measurements.

Leaf area index measured at maximum plant height, when canopy cover was fully developed and still green, decreased with increasing salinity (Table 2). At an effective salinity of 1.8 dS m^{-1}, average LAI was 2.47, whereas at 7.2 dS m^{-1} it was 1.15. Plant height was 32 cm less in higher salinity plots (Table 2) decreasing by 4.8 cm per unit increase in EC_e (Bassil, 2000). Plant population was not affected by salinity because the number of plants per length of row harvested was similar across the entire range of salinity.

There were significant differences in total sub-sample plant biomass between high and low salt plots (Table 2). Total sub-sample biomass declined significantly with increasing salinity over the range 1.8 to 7.2 dS m^{-1}. Average total sub-sample biomass was 570 and 1019 g m^{-2} for saline and non-saline plots, respectively. Plants grown in saline plots produced only 56% of the dry matter of control plants, on average. In particular, the ratio

Table 2
Safflower plant characteristics at high and low soil salinity[a]

Characteristic	EC_e (dS m^{-1})[b]	
	2.01 (0.16)[c]	7.13 (0.20)
Total plant weight (g m^{-2})	1018.5 (83.6)	569.8 (24.3)
Stem weight (g m^{-2})	461.6 (47.9)	129.4 (16.0)
Capitula weight (g m^{-2})	556.9 (35.8)	440.4 (17.1)
Seed weight (g m^{-2})	200.9 (21.2)	209.2 (8.5)
1000 seed weight (g m^{-2})	32.3 (0.77)	35.1 (0.35)
Average seed yield (kg ha^{-1})	2910 (98)	2830 (142)
WUE (kg seed mm^{-1} water)[d]	5.49	6.46
Number of plants (2 m^{-1})	47.0 (4.7)	46.3 (3.8)
Height (cm)	109.2 (3.8)	77.1 (0.9)
Leaf area index[e]	2.47 (0.16)	1.15 (0.02)
Harvest index[f]	0.20 (0.01)	0.34 (0.04)
Capitula type and number[g]	227, 249, 5, 2	235, 100, 0, 0

[a] Values determined from 2 m by one row sub-samples collected prior to harvest.

[b] Effective salinity: average of two cores per plot; nine, 30 cm samples to 2.7 m depth.

[c] Numbers in parenthesis are standard errors; $n = 3$.

[d] Water use efficiency defined as kg seed yield per mm water used (Hauck, 1984). Water use values used in the calculation were 438 and 530 mm for EC_e of 2.01 and 7.13 dS m^{-1}, respectively.

[e] EC_e range is 1.8 to 7.2 dS m^{-1}; $n = 6$.

[f] Estimated as the ration seed weight to total plant weight.

[g] Numbers designate primary, secondary, tertiary and quaternary capitula, respectively.

of stem weight to total biomass was reduced by half from 0.45 to 0.23 in saline plots. The ratio of the weight of capitula to total plant weight increased from 0.55 in the non-saline to 0.78 in the saline plots (Table 2). The decline in mature capitula dry weight was not as pronounced as the stem dry weight reduction at high effective salinity. Furthermore, plants in low salt plots formed more tertiary and quaternary buds (Table 2).

Harvest index increased with increasing salinity (Table 2). Most of the shift was accounted for by a reduction in stem weight rather than in bud weight. For these reasons, safflower yield was not adversely affected by increased soil salinity (Fig. 1), even at soil EC_e greater than 7 dS m^{-1}. One thousand seed weight increased slightly with increasing salinity (Table 2). Oil content was weakly ($r^2 = 0.50$) correlated with EC_e, increasing by 0.33% per unit increase in EC_e (Fig. 2). An average of 41% was close to Seedtec's reported average (42%) for this cultivar. Oil yield was also not adversely affected by salinity within the range in effective salinity reported in this experiment (Fig. 2).

3.2. Nitrogen

Large differences in soil NO_3–N existed in plots because of a history of irrigation with varying amounts of shallow well water (Shennan et al., 1995; Kaffka et al., 1999). Given the large differences in residual soil NO_3–N across the range in salinity, it was necessary to determine whether safflower grown in non-saline (low N) plots was N limited, and whether any interactions existed between residual N, effective EC_e, and plant growth. The analyses of soil samples for residual soil NO_3–N with depth, during this experiment, confirmed that saline plots contained significant amounts of NO_3–N (Fig. 3). Supplemental fertilization of low-salinity plots resulted in similar levels of leaf tissue N concentration (Fig. 4). Total leaf N did not correlate with effective EC_e at two dates (Fig. 4) suggesting that safflower grown in non-saline plots was not N limited in this experiment.

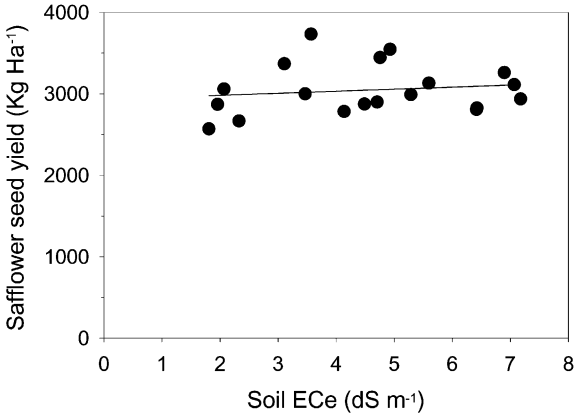

Fig. 1. Seed yield of safflower grown in a salinity gradient varying in effective EC_e (average of pre-plant and post-harvest soil samples, 0–2.7 m) from 2.1 to 7.2 dS m^{-1}. Seed yield = 2930 + 25(EC_e); $r^2 = 0.021$. Data points were obtained by harvesting 14 m of four rows with a modified combine plot harvester, and represent individual plots.

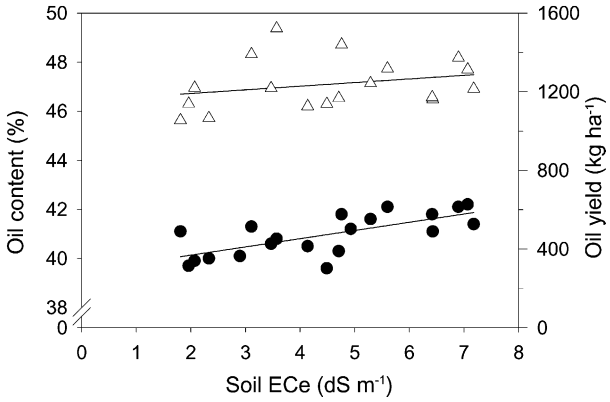

Fig. 2. Oil content (●) and oil yield (△) of safflower grown in soil with varying salinity. Effective EC_e (average of pre-plant and post-harvest soil samples, 0–2.7 m) ranged from 2.1 to 7.2 dS m^{-1}. Oil content was analyzed using NMR and averaged 41% across all plots. Regression equations are as follows: oil% $= 39.5 + 0.33(EC_e)$; $r^2 = 0.50$; oil yield $= 1150 + 18.5(EC_e)$; $r^2 = 0.06$. Data points represent individual plots.

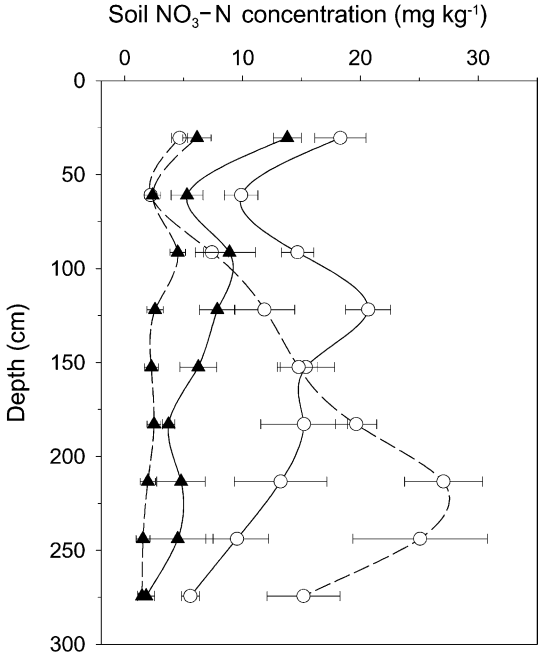

Fig. 3. Averaged (0–2.7 m) pre-plant (—) and post-harvest (– –) NO_3–N concentration with depth for saline (○) and non-saline (▲) plots. Effective EC_e for pre-plant and post-harvest was 2.2 and 2.0 dS m^{-1} and 6.5 and 7.3 dS m^{-1} for non-saline and saline plots, respectively. Error bars are S.E.; $n = 5$ for non-saline and $n = 7$ for saline plots.

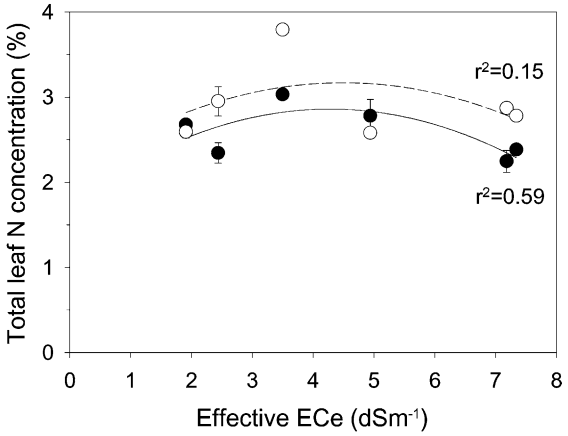

Fig. 4. Total leaf N concentration of safflower (leaves) grown in a salinity gradient sampled on two dates (23rd June 1998 (●, —); 7th June 1998 (○, – –)). Effective EC_e (average of pre-plant and post-harvest soil samples, 0–2.7 m) ranged from 2.1 to 7.2 dS m^{-1}. Error bars are S.E.; $n = 9$.

4. Discussion

4.1. Plant response to salinity

Plant water potential determinations resulted in significant differences between dates and levels of effective salinity. To the best of our knowledge, there has been no previous determination of safflower water potential reported. Using the flower head and part of the stem for water potential determinations seemed reasonable given that safflower leaves have no real petiole (Weiss, 1971). The difference between water potential values over time was greater in saline than non-saline plots at pre-dawn and mid-day. Water potential results are likely to be minimum estimates due to differences in xylem sap solute potential and relative capitula growth rates between plants in saline and non-saline plots. In this experiment xylem sap solute potential was not determined (see Hsiao, 1990). We did not measure differences in stomatal conductance in these plots, although differences in total biomass suggest such a response.

Even though total biomass was reduced under saline conditions, stress was not severe enough to limit seed yield. Safflower response to increasing salinity included reduced plant height, biomass, leaf area, capitula number and order, and earlier maturation. At the highest salinity levels, safflower produced half the biomass of plants grown in non-saline plots. Because safflower grown in salty plots formed fewer secondary and tertiary buds, an increase in effective salinity seemed to shorten the bud development period. Our data indicate that for every unit increase in EC_e, time to full bloom was hastened by (approximately) 3 days. In contrast Francois and Bernstein (1964) report that the rate to crop maturity was increased by 1 week for every three to four unit increase in EC_e (approximately 2.5 days). Because of the mild weather conditions during the early part of the growing season in this trial, the period and intensity of safflower's exposure to salinity may have been shortened or otherwise lessened. One factor influencing salinity tolerance

is the duration of exposure to salinity (Munns and Termaat, 1998; Läuchli and Epstein, 1990). Nevertheless, most of the findings from this experiment are in close agreement with results reported elsewhere (Francois and Bernstein, 1964; Yermanos et al., 1964; Irving et al., 1988). Harvest index increased with increasing salinity mainly due to a reduction in the stem to total biomass ratio. Flower bud weight was significantly less affected by salinity. Safflower, therefore, appears to have the capacity to adjust harvest index in response to moderate levels of soil and irrigation water salinity.

Overall, seed yields are considered to be similar to normal years and conditions in the western SJV (Kaffka and Kearney, 1998). Seed yield was not affected by salinity in this experiment. Safflower responds to salinity with altered dry matter partitioning. Other reports have shown that intermediate levels of salinity can enhance growth and yield with some reports attributing this yield increase to beneficial effects of sodium (Aslam, 1975; Devi et al., 1980; Rai, 1977). Most previous reports, however, have indicated that yield reductions occur at lower salinity levels than were found in this experiment. In artificially salinized plots, Francois and Bernstein (1964) found that at 7, 11 and 14 dS m^{-1} relative yield reductions were 10, 25, and 50%, respectively. Other estimates predict a 50% yield decrease on soils with an EC_e of 9.9 dS m^{-1} (Ayers and Westcot, 1976). For safflower established with low EC_e water (0.9 dS m^{-1}) for the first 2–3 weeks, and irrigated subsequently with saline water containing a 2:1 ratio of NaCl to $CaCl_2$, pooled yield decreases of primary capitula of four cultivars were 75 and 29% of the control for EC_i of 13.5 and 20.5 dS m^{-1}, respectively (Irving et al., 1988). Yield decreases of secondary capitula were greater when compared to the control. However, at an EC_i of 7.5 dS m^{-1}, yield of primary and secondary capitula increased by 25 and 14% relative to the control (Irving et al., 1988). In experiments where safflower was preceded by 2 years of cotton irrigated with saline water ($EC_i = 11.6$ dS m^{-1}), safflower yields decreased by 40% in subsequent cycles of the rotation. The yield decreases were attributed to poor germination and emergence in salinized plots (Rains et al., 1987).

Results from this experiment indicated that safflower can tolerate slightly higher levels of soil and water salinity than previously reported. Some of this increased tolerance is thought to have been due to mild weather that reduces the effects of salinity. Furthermore, gypsiferous soils have a high Ca^{2+}:Na^{+} ratio, which reduces the effects of salinity compared to Na^{+} dominated soils (Tanji, 1990).

In this experiment, oil content in seeds was not adversely affected by salinity. In contrast, Yermanos et al. (1964), Francois and Bernstein (1964), Francois et al. (1964), Irving et al. (1988) and Beke and Volkmar (1995) all report a decrease in oil percent with higher levels of effective soil salinity. Francois and Bernstein (1964) have attributed this oil decrease to an increase in hull percentage caused by faster physiological maturity under salt stress. Hull percent was not determined in this experiment.

4.2. Nitrogen

In saline plots there were large amounts of NO_3–N (Fig. 3). No significant reduction in soil N due to safflower growth was detected. The change in soil N concentration in saline plots was small compared to the amounts of residual N, N sampling variation, and N use by plants in low-salinity plots. Because safflower growth was reduced under saline

conditions, less N demand and more deep percolation occurred (Fig. 3). Any N that was not utilized was probably leached from the upper root zone. Pang and Letey (1998) propose a model that perpetuates N leaching beyond the root zone (making it plant unavailable), under saline conditions that reduce plant (root) growth. NO_3–N accumulation in the bottom of the root zone at the post-harvest period was observed, consistent with the mechanism proposed by Pang and Letey (1998) and was likely mobilized by water movement, specifically drainage (Bassil and Kaffka, 2001). Despite any N leaching that may have occurred under high-salinity, safflower was not N limited because total leaf N percent is within the normal physiological range of most plants (Marschner, 1995) and was similar across treatments. High levels of residual N do not seem to affect safflower's response to salinity even when correlated with plant N nutrition directly (Shalhevet, 1994; Grattan and Grieve, 1999).

5. Conclusions

Weather conditions during most of the early part of the growing season were unusually cool due to the El Niño climate pattern, with above average relative humidity (Bassil and Kaffka, 2001). The effects of soil salinity under these conditions were severe enough to affect dry matter partitioning, and therefore, promote a larger harvest index, but not sufficient to reduce seed yield or oil content. Safflower responded to salinity by reducing plant height, capitula number and order, and leaf area. Maturity was advanced with increasing salinity, but seed yields were not affected. Safflower appears to have the capacity to adjust harvest index in response to moderate levels of soil and irrigation water salinity. Saline drainage or shallow well water can be used to irrigate safflower without yield loss if the effective salinity levels of soil and water are less than 7.2 dS m^{-1}.

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