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Long-term effects of saline irrigation water on 'Valencia' orange trees: relationships between growth and yield, and salt levels in soil and leaves

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Abstract. This study documents changes in yield, growth, soil salinity (EC_e) and leaf sodium (Na) and chlorine (Cl) concentrations in mature Valencia orange [*Citrus sinensis* (L.Osbeck)] trees on sweet orange (*Citrus sinensis*) rootstock in response to increased levels of Na and Cl in irrigation water. Four levels of salt, ranging from the river-water control (0.44 dS/m) to 2.50 dS/m, were applied over a 9-year period through an under-tree microsprinkler system to trees in the Sunraysia area of the Murray Valley in south-eastern Australia. A salt-balance model showed that evapotranspiration was reduced by salinity, whereas leaching fractions increased from an average 24% in the control to 51% in the most saline treatment. The high leaching fractions were achieved as a result of freely draining soils and good irrigation management, and allowed us to maintain low to moderate levels of soil salinity throughout the trial and minimised the effect of salt treatment on fruit yield. Soil salinity increased almost linearly in response to irrigation-water salinity during the first year, and fluctuated seasonally thereafter; however, very few readings exceeded 3 dS/m, even in the highest treatments. By contrast, leaf Na and Cl concentrations in the highest salt treatment continued to increase over the first 4 years. The relationship between yield and soil salinity was extremely weak, but yield did decrease as foliar concentrations of Na and Cl increased: in Year 9, leaf Na in the highest treatment relative to the control was associated with a predicted reduction of 17% in yield and 59% in annual trunk-diameter growth.

Additional keywords: salinity, citrus, leaching, nutrients, nitrogen, potassium, phosphorus.

Introduction

Citrus is regarded as a salt-sensitive crop (Maas and Hoffman 1977; Gutteridge, Haskins, Davey 1999), but few studies have presented information on long-term yield responses (Maas 1993). Because plants respond to salinity in the soil solution, rather than to irrigation-water salinity *per se*, the crop response is usually expressed in relation to salinity of the saturated soil extract (Maas 1993). The relationship between salinity in the soil solution and salinity of applied water is determined by the leaching fraction, which is influenced by irrigation management and soil properties as well as by salinity in the applied water. However, response of citrus to salinity of the soil solution has also varied among studies (Bingham *et al*. 1974; Cerdá *et al*. 1990; Dasberg *et al*. 1991) for reasons including (*i*) both rootstocks and scions vary in their salt tolerance and the degree to which they are able to limit accumulation of sodium (Na) and chlorine (Cl) ions in leaves (Grieve and Walker 1983; Maas 1993; Storey and Walker 1998; Levy and Syvertsen 2004), (*ii*) salinity is generally more detrimental to tree growth in semi-arid climates than in subtropical ones (Maas 1993), (*iii*) the response varies with duration of exposure to salt (Bingham *et al*. 1974; Dasberg *et al*. 1991; Grieve *et al*. 2007), and (*iv*) soil salinity levels vary in space and time, so that correlating them with plant attributes is complicated (Maas 1993).

The ultimate cause of growth and yield reductions in citrus exposed to saline conditions is not clear. Some studies indicate that the effect of salinity is primarily mediated by osmotic effects (Maas 1993), in which case, salinity in the soil solution is the most important predictor. Other studies, however, have implicated the toxic effects of Na and/or Cl ions (Cole 1985; Lloyd *et al*. 1987, 1990; Lloyd and Howie 1989). It may be that toxic ionic effects are most important in rootstock/scion combinations that are poor excluders of Na and Cl ions, but osmotic effects predominate in combinations that effectively exclude Na and Cl ions from leaves.

The relationship between soil and plant salinity and growth and yield of citrus trees is examined in this paper, which complements the report by Grieve *et al*. (2007) on the response of growth and yield to salinity in irrigation water. In this experiment, irrigation water containing 4 levels of NaCl was applied to field-grown Valencia orange trees in the Sunraysia region of the Murray Valley, south-eastern Australia. Grieve *et al*. (2007) found that saline irrigation water reduced growth, and the severity of the effect increased with duration of salinisation. By contrast, yield was highest in the intermediate

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salt treatments, and was only slightly reduced by the highest salt treatment. There were some minor effects on fruit quality. Salinised treatments increased juice sugar content but reduced fruit size, juice content, and total soluble solids yield. Overall, the adverse effects of salt treatment were surprisingly small, probably because of a combination of factors: (*i*) irrigations were applied weekly (during summer) or as required, with amounts calculated from measurements of potential evapotranspiration and rainfall; (*ii*) under-tree irrigation systems avoided wetting most leaves and associated foliar uptake of salt; (*iii*) soils had excellent natural drainage. In the present paper, we examine, for the same trees, the response of growth and yield to salinity levels in soil and leaves, as well as the changes in soil salinity and plant nutrient levels when saline water is applied. We also estimate orchard evapotranspiration and leaching fractions from measurements of soil salinity at regular intervals throughout the trial, together with measurements of other soil properties, rainfall, water applications, and irrigation-water salinity.

Materials and methods

Study site and experimental design

The trial was conducted at the Agricultural Research and Advisory Station, Dareton (34°04′S, 142°02′E), in south-western New South Wales. Climate is semi-arid. The town of Wentworth, 10-km distant, receives 286 mm mean annual rainfall that is, on average, evenly distributed through the year. However, rainfall is most effective during winter because evaporation is lower than in summer. Summers are hot and winters cool; long-term mean monthly maximum and minimum temperatures for January are 32.9°C and 17.1°C, and for July are 15.6°C and 4.9°C, respectively (Bureau of Meteorology 2006). The soil at the study site is a Tiltao sand (Northcote and Boehm 1949) (classified as Uc5.12 according to Northcote 1979) with a structureless, calcareous A horizon to 1.0–1.2 m and a sandy loam B horizon.

The experimental orchard was planted in 1960 and consisted of 34 rows, each 100 m long. Trees were spaced at either 7.3 by 7.3 m (single-planted) or 7.3 by 3.7 m (double-planted). Double-planted trees formed hedgerows running in a north–south direction. The orchard comprised Valencia orange [*Citrus sinensis* (L. Osbeck)] on sweet orange (*C. sinensis*) rootstock. It had previously been used for spacing and irrigation trials, so the 4 salinity treatments were imposed orthogonally to previous treatments. Treatment plots were 2 rows wide, and comprised either 4 single-planted or 10 double-planted trees. Buffer rows on either side of the plot rows and buffer trees within rows received the same salt treatment as the plots they enclosed. The 32 treatment plots were arranged in two 4 × 4 Latin squares, so that each treatment was represented once in each row. In 4 plots, alternate trees were on trifoliate orange rootstock, so were excluded from our analyses. Thus, for each salinity treatment, there were 5 replicates of single-planted trees and 2 replicates of double-planted trees, and there was less uncertainty associated with estimations for single-planted than for double-planted trees.

The 4 salinity treatments commenced in September 1982 and continued until the end of May 1991. The Year 1 harvest thus occurred at the end of 1983. The salt treatments comprised river water either untreated as a control (Tr0; mean EC_i over the 9 years of the trial was 0.44 dS/m) or injected with NaCl solution (200 g/L) to give mean EC_i values of 1.28 (Tr1), 1.96 (Tr2), and 2.50 dS/m (Tr3). Corresponding NaCl concentrations were ~2.7, 9.7, 15.6, and 20.6 meq/L for Tr0 to Tr3, respectively. Mean EC_i was estimated each season by measuring the conductivity of irrigation water sampled continuously from all treatments during each irrigation, and weighting the readings for the amount of water applied at each irrigation.

The EC_i for Tr0 was slightly higher than for river water (mean EC_i 0.38 dS/m) because of residual salt in the main irrigation supply line after salinised treatments were applied. The sodium adsorption ratio in the applied water ranged from 2 (Tr0) to 30 (Tr3). A detailed analysis of the added salt showed it to be >99% NaCl, with traces of Ca and Mg. No boron was detected. Calcium was not added to salinised treatments because increases in salinity in the River Murray are primarily due to increases in NaCl, and are accompanied by increases in sodicity (Gutteridge, Haskins, Davey 1970).

Management

The irrigation system comprised pressure-compensated microsprinklers spaced 3.7 m apart in the tree line, and located 1.85 m from the tree trunks. These gave a continuous wetted strip about 4 m wide (54% of the total area of the planting). Irrigations were scheduled using tensiometer readings as a guide. During the summer months (November–March) the trees were irrigated weekly, and during the remainder of the year, trees were watered when the tensiometer reading at 0.60-m depth reached −25 to −30 kPa. This irrigation schedule had been shown to lead to high productivity and water-use efficiency in this orchard (Grieve 1989). Irrigation applications averaged 44 mm (calculated on a full-area basis) applied on average 28 times per year. All salinity treatments were given the same total amount of water. Total irrigation applications and rainfall are shown in Table 1.

Major nutrients were supplied through the irrigation system at annual rates of 158 kg/ha N (expressed on a full-area basis) (as urea and monoammonium phosphate), 38 kg/ha P (as monoammonium phosphate), and 40 kg/ha K (as potassium sulfate). Fertiliser was injected into the irrigation water during the last part of the irrigation period to avoid losses due to leaching. A staged monthly program was followed (August 35% of total, September 20%, October–December 15% per month). Standard district management practices, including a total weed-control program, were followed.

Plant and soil measurements

Yield and total fruit number were recorded annually for each plot. Trunk circumference 0.15 m above the graft union was measured annually, from which diameter increment was calculated as an index of tree growth.

Sixty mature spring-flush leaves were sampled from each plot at chest height in late February each year for measurement of leaf salt and nutrient concentrations. Leaves were oven-dried for at least 24 h at 70°C, then ground to a fine powder. Leaf Cl concentration was determined between 1983 and 1991 (Years 1–9) by silver ion titration of aqueous extracts using

Table 1. Irrigation water applications (mm), effective rainfall (mm), and evapotranspiration (mm) for the 4 salt treatments in each interval

All amounts are in mm depth, averaged over the whole ground area. The effects of salt ($F_{3,20} = 21.24$) and interval ($F_{8,160} = 8.18$) were both highly significant ($P < 0.001$), but that of spacing ($F_{1,20} = 0.43$) was not, nor was the salt × spacing interaction significant

Interval	Irrigation water applied	Effective rainfall	Evapotranspiration by trees receiving:			
			Tr0	Tr1	Tr2	Tr3
Aug. 82–Aug. 83	1430	70	1161	857	518	547
Aug. 83–Aug. 84	1095	171	974	876	665	695
Aug. 84–May 85	1135	10	902	654	530	641
May 85–July 86	1310	89	1122	604	599	636
July 86–May 87	949	38	727	569	440	350
May 87–July 88	1370	101	1014	896	769	729
July 88–May 89	1246	247	1131	817	828	714
May 89–June 90	1136	79	952	934	561	738
June 90–Apr. 91	1074	68	951	800	705	782
Mean per year	*1194*	*97*	*993*	*779*	*624*	*648*

a chloridometer (Buchler, Fort Lee, NJ, USA), and leaf Na was measured from 1984 to 1991 using flame emission photometry. Leaf N, P, K, Ca, and Mg were measured only between 1984 and 1988 inclusive (i.e. Years 2–6) because of resource limitations. Foliar P, K, Ca, and Mg were analysed by X-ray fluorescence and total N was analysed by the Kjeldahl method.

In July 1983, soil samples were taken at depths of 0.3, 0.6, and 0.9 m from a grid of 8 holes to find a position where salinity levels were representative of the bulk of the root-zone, suitable to use as a standard sampling position. After measuring the electrical conductivity of 1 : 5 soil : water extracts ($EC_{1:5}$) of these samples, we chose a position midway between the trunk and the sprinkler, 1 m out from the tree line (a distance of 1.36 m from both), at 0.9-m depth. Each year, soil was sampled from this standard position, and the electrical conductivity of a saturated extract (EC_e) was measured. Sampling took place during the winter, but the month of sampling varied among years (Table 2). The different sampling time was included in the analysis to control for the gradual decline in soil salinity during winter. There was a total of 10 sampling times and thus 9 intervals for which we were able to calculate water use and leaching fraction.

Table 2. Leaching fractions, as a proportion of irrigation plus rainwater, for the 4 salt treatments in each interval

Intervals were defined by times at which soil was sampled, and were of unequal length. Repeated-measures ANOVA showed that the effects of salt ($F_{3,20} = 22.6$) and interval ($F_{8,160} = 6.33$) were both highly significant ($P < 0.001$), but the effect of spacing ($F_{1,20} = 0.66$) was not, nor was the salt × spacing interaction significant

Interval	Tr0	Tr1	Tr2	Tr3
Aug. 82–Aug. 83	0.231	0.438	0.669	0.649
Aug. 83–Aug. 84	0.246	0.328	0.505	0.480
Aug. 84–May 85	0.213	0.431	0.539	0.442
May 85–July 86	0.204	0.585	0.589	0.562
July 86–May 87	0.268	0.431	0.564	0.656
May 87–July 88	0.321	0.404	0.493	0.520
July 88–May 89	0.262	0.489	0.482	0.565
May 89–June 90	0.223	0.238	0.555	0.404
June 90–Apr. 91	0.171	0.308	0.393	0.324
Mean per year	*0.238*	*0.406*	*0.532*	*0.511*

Estimation of leaching fraction

Leaching fraction (LF) at the standard position for each plot at each of the 10 intervals was calculated by:

$$\mathrm{LF} = Q_{\mathrm{L}}/(Q_i + Q_r) \qquad (1)$$

where Q_{L} is quantity of water leached at depth z (mm), Q_i is quantity of irrigation water (mm), and Q_r is effective rainfall (mm), defined as the amount in excess of 10 mm (September–April) or 5 mm (May–August).

Q_{L} in the wetted strip was calculated using an equation based on a salt-balance model, as described by Prior *et al.* (1992). The method is based on estimating annual addition of salts to the root-zone and annual changes in salt storage in the root-zone:

$$Q_{\mathrm{L}} = \frac{2\theta_{g(z)}}{\theta_{\mathrm{SP}(z)}}\left[\frac{EC_i Q_i - z\rho\bar{\theta}_{\mathrm{SP}(0\text{-}z)}\alpha(E_{e(z)t2} - EC_{e(z)t1})}{E_{e(z)t2} + EC_{e(z)t1}}\right] \qquad (2)$$

where $\theta_{g(z)}$ is the mean gravimetric water content (g H_2O/g soil) at depth z during the time that leaching occurs, θ_{SP} is the gravimetric water content at saturation of the soil paste, $\bar{\theta}_{\mathrm{SP}(0\text{-}z)}$ is mean θ_{SP} over depth (0-z), EC_i is salinity of irrigation water (dS/m), Q_i is depth of irrigation water (mm), z is the base of the root-zone (mm depth), ρ is average bulk density of the root-zone (g soil per cm^3), α is an empirical factor relating the average EC_e of the rooting volume above z, $EC_{e(0\text{-}z)}$, to the EC_e at depth z, i.e. $EC_{e(0\text{-}z)} = \alpha\, EC_{e(z)}$, and $EC_{e(z)t}$ is electrical conductivity of a saturated soil extract sampled at depth z at time t.

EC_i and Q_i were known from irrigation records, and $EC_{e(z)t}$ from the soil sampling described above. We considered the root-zone to extend 2.0 m either side of the tree line to a depth of 1.0 m, since this was where most of the water uptake occurred in micro-irrigated trees (Grieve 1989). To quantify the remaining parameters, in March 1991 we sampled 4 × 9-hole grids at 0.15, 0.3, 0.45, 0.6, 0.75, and 0.9 m depth in 2 plots each of Tr0 and Tr3, and measured EC_e, θ_g, θ_{SP}, and ρ. The parameter α, which related the mean root-zone EC_e to that at our standard sampling position, was calculated to be 1.17. To estimate θ_{SP}, soil from one sample per plot taken from 0.3, 0.6, and 0.9 m depth was air-dried, ground, and placed on a blotting-paper suction plate (McIntyre 1974) with a 0.02-m suction. Gravimetric water content of this saturated soil was measured, and the ratio $\theta_g : \theta_{SP}$ was found to average 0.380. Bulk density was measured by carefully taking soil cores of a known volume and drying them at 105°C before weighing; it averaged 1.67 g soil/cm^3.

The leaching calculations only (Eqns 1 and 2) used $Q_{i\text{-wetted}}$; this was calculated as the volume applied by the irrigation system to the wetted strip, taken to be 4 m wide, and was thus average irrigation depth × (7.32 m/4 m). It was assumed that no leaching occurred in the non-wetted fraction, which received only rainwater.

Evapotranspiration from the 4-m-wide wetted zone, which received both irrigation and rainfall, was calculated as $(1 - \mathrm{LF})(Q_{i\text{-wetted}} + Q_r)$. Evapotranspiration from the 3.32-m-wide non-wetted zone was assumed to be equivalent to the rainfall received, Q_r. An area-weighted average (in mm) was then obtained:

$$[(1 - \mathrm{LF})(Q_{i\text{-wetted}} + Q_r) * 4 + Q_r * 3.32]/7.32 \qquad (3)$$

Statistical analyses

Our analytical approach was to use multi-model inference based on information theory and model averaging. Akaike's information criterion for small samples (AIC$_c$) was used to rank and weight the models (Burnham and Anderson 2001, 2002). A set of candidate models was developed to describe relationships between each response variable and possible explanatory variables. Each candidate model set included a 'null' model, which describes the case where none of the possible explanatory variables has an effect. The AIC$_c$ identifies the model(s) most strongly supported by the databased on the bias-corrected, maximised log-likelihood of the fitted model and a penalty for the number of parameters used (Burnham and Anderson 2002). The Akaike weights represent the weight of evidence in favour of a particular model as being the best model in the set. Designation of a single 'best' model is often unsatisfactory when there are several closely related models (Burnham and Anderson 2002), but model averaging can provide a more stable and less biased estimate of effect size than any single best model. All mixed effects models and associated analyses were derived using the R statistical package *v.* 2.2.0 (R Development Core Team 2005).

We used this multi-model approach to assess the importance and magnitude of the effects of salt treatment and tree spacing on the EC_e of soil and Na, Cl, N, P, K, Ca, and Mg concentrations of leaves from each plot over several years (see below). We needed to consider that effects of salt may change with duration of salt treatment (Bingham *et al.* 1974; Dasberg *et al.* 1991; Grieve *et al.* 2007), so some models included the term 'duration plus duration by salt treatment' and possible interactions between factors. Salt treatment was treated as a categorical factor because the response to it was often non-linear. Spacing was also a categorical factor, but duration of salt was a continuous one. The full set of candidate models is shown in Table 3, and was the same as that used for yield and yield attributes by Grieve *et al.* (2007). It was necessary to use mixed effects models to account for the repeated-measures of each attribute; year was thus a random effect that accounted for stochastic temporal variation, and 'duration' incorporated trends with time. Because soil

Table 3. AIC$_c$ weights for the most strongly supported models describing the response of EC_e or each leaf nutrient to salinity treatment

AIC$_c$ weights indicate the relative weights of models based on the bias-corrected, maximised log-likelihood of the fitted model and a penalty for the number of parameters used (see Methods). The fixed effects of all models in the candidate model set are shown, along with AIC$_c$ weights. For clarity, AIC$_c$ weights are shown only for models receiving ≥10% support, and for the null models (italicised). 'Spacing' and 'Salt' are categorical variables, and 'Duration' of salt treatment is a continuous variable to account for possible progressive effects of salinity. In all models, 'Year' was included as a random effect to account for stochastic differences between years, and spatial correlations were accounted for in the models. The last 8 models, that feature Month as a continuous variable, are applicable only to the response variable EC_e, because soil was sampled at different times during the winter months, but leaves were always sampled in February. EC_e decreases over the winter months due to leaching by winter rainfall. The operator '*' indicates 'main effects and interactions'

Response variable:	EC_e	Cl	Na	N	P	K	Ca	Mg
Model								
Spacing * Salt + Duration * Salt		0.894	1.000		0.128	1.000		0.901
Spacing + Duration * Salt				0.493			0.206	
Spacing * Salt					0.789			
Spacing + Salt				0.200				
Spacing								
Salt * Duration				0.154			0.591	
Salt							0.117	
Null	*3 × 10^{-25}*	*2 × 10^{-46}*	*3 × 10^{-67}*	*1 × 10^{-8}*	*1 × 10^{-6}*	*1 × 10^{-22}*	*1 × 10^{-11}*	*4 × 10^{-8}*
Month + Spacing * Salt + Duration * Salt								
Month + Spacing + Duration * Salt								
Month + Spacing * Salt								
Month + spacing + Salt	0.292							
Month + Spacing								
Month + Salt * Duration								
Month + Salt	0.537							
Month								

was sampled at different times, and soil salinity progressively decreased through the winter, we used month of sampling as a continuous variable in the analysis of the relationship between EC_e and salt treatment. Possible spatial correlations were incorporated in the models by using a linear correlation argument (form = rows + columns). In practice, spatial effects were minimal, barely extending into adjacent plots along rows, and not across rows (the range of influence was 3–4 row spacings, and plot centres were 4 row spacings apart across rows, and 3 row spacings apart down rows). Log-transformations of leaf Na and Cl were required to maintain constant error variance. For each attribute, we used the weighted averaged coefficients of all models receiving ≥10% of the AIC$_c$ weight (Table 3) to estimate the magnitude of effects of salt, spacing, and duration of salt treatment. These coefficients were used to calculate the model predictions presented in the figures and tables.

We also used linear mixed effects models to describe the relationship between the response variables yield and trunk diameter increment, and the continuous explanatory variables EC_e, leaf Cl, and leaf Na. Square-root transformations of diameter increments were required to maintain constant error variance.The global models included the categorical factor, tree spacing, and the continuous variable, duration of salt treatment, and some interactions. For the relationships with EC_e, we included month of sampling as a continuous variable. The candidate model sets are shown in Table 4. Year was retained as a random factor, but we did not consider possible spatial correlations in these analyses, given they were not important in the response of any parameters to irrigation-water salinity.

The effects of salt treatment and tree spacing on evapotranspiration and leaching fraction over the 9 years of the trial were tested using repeated-measures analysis of variance using Statistica *v.* 7 (Statsoft Inc., OK, USA). It was not meaningful to model the effect of duration of salt treatment because measurement intervals were unequal; thus, only simple statistical analysis was required. Data transformation was not required.

Results

Effects of irrigation-water salinity on EC_e and leaf Na, Cl, and nutrient concentrations

EC_e increased almost linearly in response to irrigation-water salinity (Fig. 1), but there was virtually no support for models incorporating a trend with time (Table 3), indicating that this response occurred within a year of salt application. Indeed, most of the fluctuations in Fig. 1 are due to changes in the month of sampling, with generally higher EC_e values in samples taken early than late in the winter. However, soil salinity was low to moderate throughout the trial, even in the highest treatment where there were few EC_e values >3 dS/m.

Leaf Na and leaf Cl concentrations increased with irrigation-water salinity, and they also increased markedly with duration of salt treatment (Fig. 1). The increase with time was especially pronounced for leaf Na; in Year 2 (the first year for which data were available), leaf Na levels in the highest treatment were <0.1%, but between Years 5 and 9, they were almost 0.5% in trees receiving the highest salt treatment (Fig. 1).

Irrigation-water salinity also affected levels of all major leaf nutrients, and for most, the effects increased with duration of salinisation. Leaf N and P were both higher in the salinised treatments, and the effect on leaf N increased with time (Fig. 2). Leaf K was scarcely affected by irrigation-water salinity in Year 2, but by Year 6, it was reduced by a predicted 36% in the

Table 4. AIC$_c$ weights for the most strongly supported models describing the relationships between the response variables, butt diameter increment or yield, and the explanatory variables EC_e, leaf Cl, or leaf Na content

AIC$_c$ weights indicate the relative weights of models based on the bias-corrected, maximised log-likelihood of the fitted model and a penalty for the number of parameters used (see Methods). The explanatory variables of all models in the candidate model set are shown, including the salinity variables (*X*, italicised). For clarity, AIC$_c$ weights are shown only for models receiving ≥10% support, and for the null model (italicised). 'Spacing' is a categorical variable, and the explanatory variables 'Month' and 'Duration' of salt treatment are continuous variables. In all models, 'Year' was included as a random effect to account for stochastic differences between years. The last 6 models, which include Month as a continuous explanatory variable, are applicable only to the response variable EC_e, because soil was sampled at different times during the winter months, but leaves were always sampled in February. EC_e decreased over the winter months due to leaching by winter rainfall. The operator '*' indicates 'main effects and interactions'

Response variable:	Butt diameter increment			Yield		
Salinity variable (*X*):	EC_e	Leaf Cl	Leaf Na	EC_e	Leaf Cl	Leaf Na
Model						
X * Duration + Spacing	0.114	0.387	0.130	0.124	0.725	
X * Duration					0.119	0.107
X + Spacing	0.136	0.566	0.870	0.221	0.103	0.224
X						0.628
Spacing				0.333		
Null	1.8×10^{-13}	6.2×10^{-13}	5.8×10^{-12}	*0.018*	*0.011*	*0.002*
Month + *X* * Duration + Spacing	0.570					
Month + *X* * Duration						
Month + *X* + Spacing	0.180			0.119		
Month + *X*						
Month + Spacing						
Month						

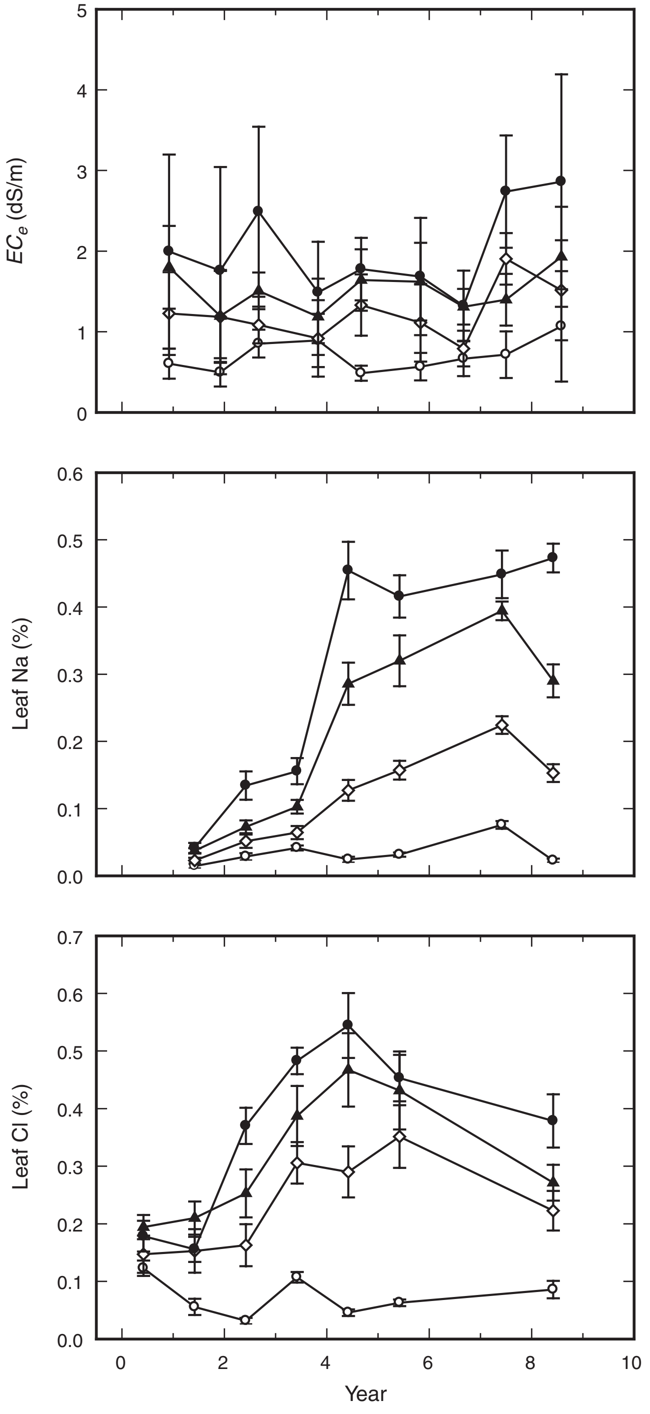

Fig. 1. The response of mean soil salinity (EC_e) and leaf Na and Cl concentrations with time to the 4 salt treatments: the control, Tr0 (open circles), Tr1 (open diamonds), Tr2 (closed triangles), and Tr3 (closed circles). Year 0 represents the commencement of salt treatments in September 1982, and bars indicate s.e.m. for each treatment.

highest treatments (Fig. 2). Leaf Ca was also reduced by salt treatment, but not to the same extent as was leaf K; the predicted reduction was 14% in Year 6. Leaf Mg in Year 6 was higher in the salinised treatments, especially for double-planted trees (Fig. 2).

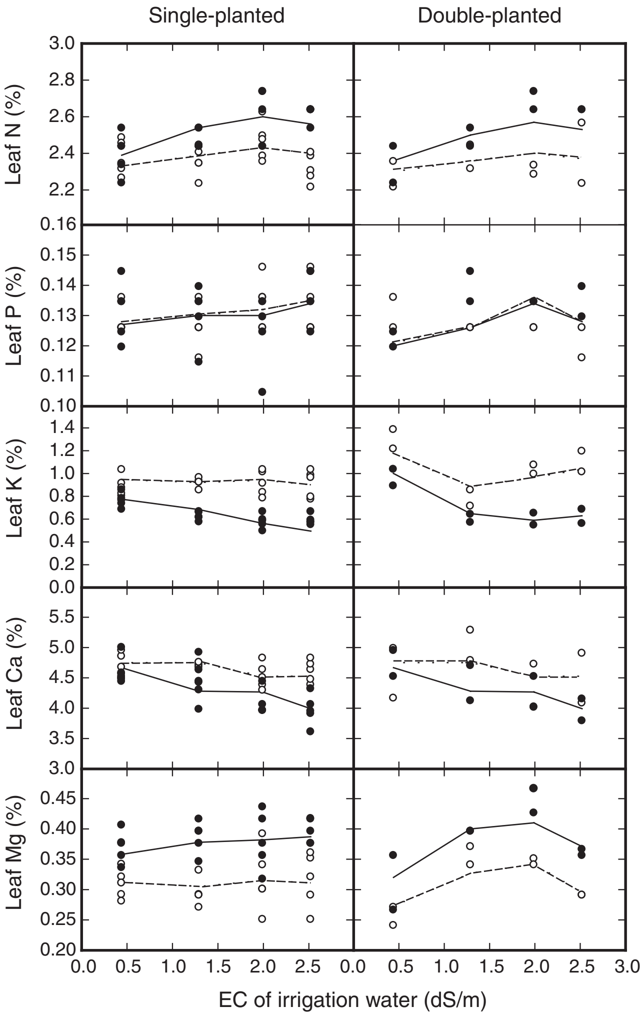

Fig. 2. Response of leaf nutrients to salt treatment in single-planted and double-planted plots. Symbols represent actual values for each plot in the first (Year 2, open circles) and last (Year 6, closed circles) years of measurement, corrected for random effects of year. Lines represent the predicted values for Year 2 (dashed) and Year 6 (solid).

Relationships between growth or yield, and EC_e, leaf Cl, or leaf Na

Annual trunk-diameter increment decreased with EC_e, and decreased with time regardless of EC_e levels (Fig. 3). Trunk-diameter increment was smaller in double-planted than in single-planted trees. Similarly, trunk-diameter increment decreased with leaf Cl, and decreased with time irrespective of leaf Cl levels (Fig. 3). However, the decrease in response to leaf Na was almost constant over the duration of the trial (Fig. 3).

Yield was generally slower than trunk-diameter increment to respond to soil and plant salinity, and effects were far less pronounced. The relationship between EC_e and yield was very weak and varied little between years or month of sampling (Fig. 4); the most strongly supported model in the candidate set did not include EC_e (Table 4). The highest EC_e of ~4.5 dS/m was associated with a predicted yield decrease of only 1%. There

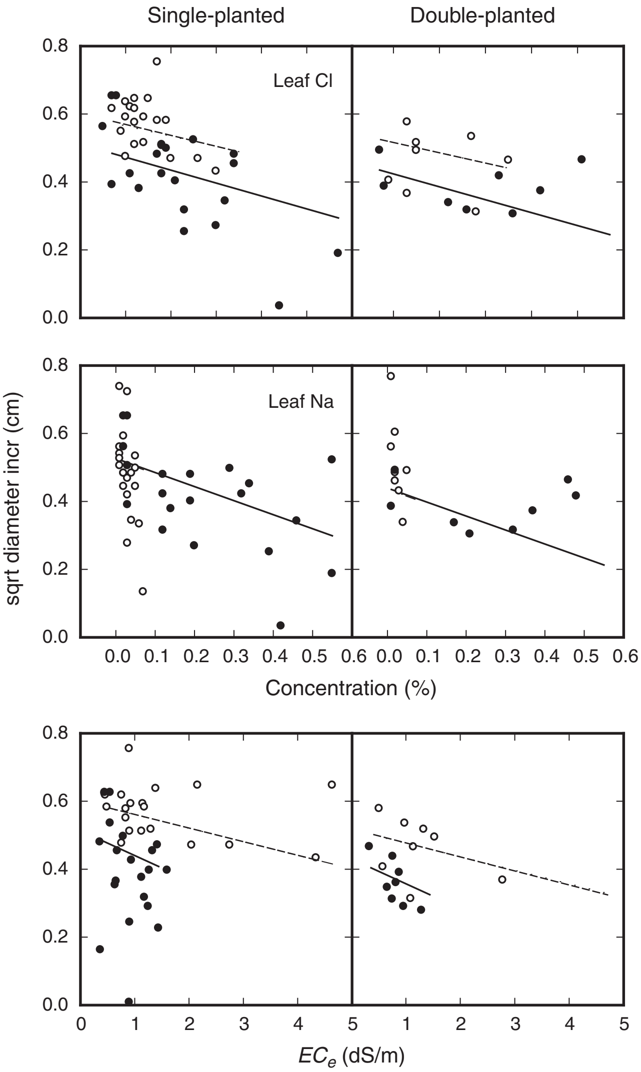

Fig. 3. Relationships between the square root of the annual trunk-diameter increment (sqrt diameter incr) and leaf Cl, leaf Na, and EC_e in single-planted and double-planted plots. Actual plot means, corrected for random effect of year, are indicated by open circles in the first (Year 1 for Cl and EC_e, Year 2 for Na) and closed circles in the last (Year 9) years of measurement. Predicted values over the appropriate data range are indicated by dashed (Years 1 or 2) and solid (Year 9) lines. The relationships differed substantially between years for both leaf Cl and EC_e, but not for leaf Na.

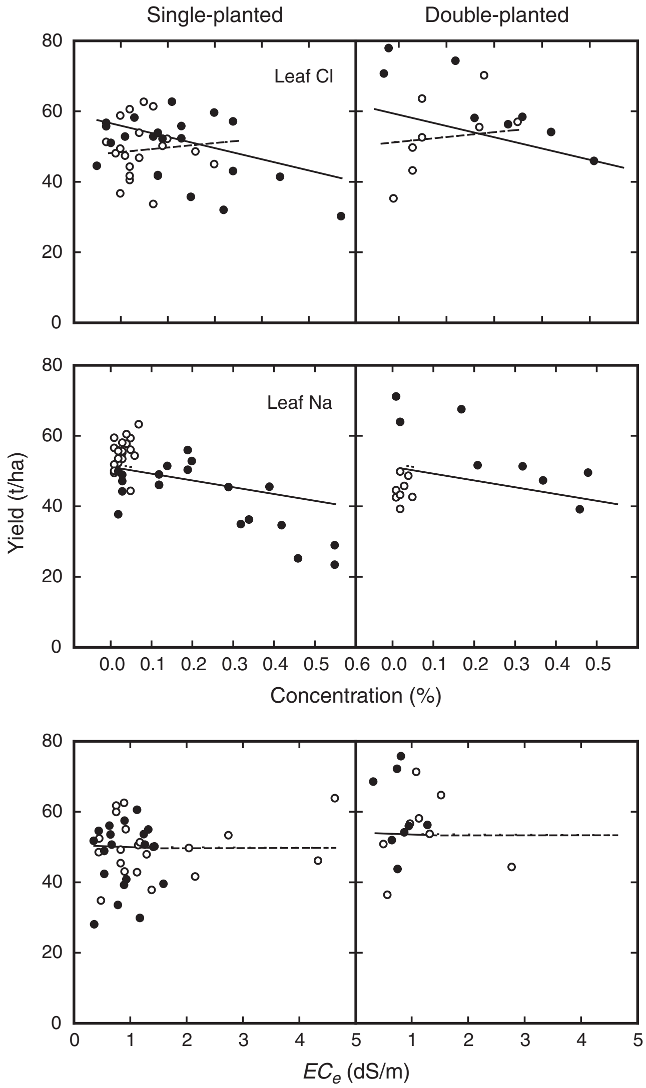

Fig. 4. Relationships between yield and leaf Cl, leaf Na, and EC_e in single-planted and double-planted plots. Actual plot means, corrected for random effect of year, are indicated by open circles in the first (Year 1 for Cl and EC_e, Year 2 for Na) and closed circles in the last (Year 9) years of measurement. Predicted values over the appropriate data range are indicated by dashed (Years 1 or 2) and solid (Year 9) lines, and are calculated from coefficients presented in Table 5. The relationships differed substantially between years only for leaf Cl.

was little relationship between leaf Cl and yield in Year 1, but in Year 9, a leaf Cl level of 0.5% was associated with a 25% decrease in predicted yield (Fig. 3). Leaf Na was uniformly very low in Year 2, but there was a much larger range in values in Year 9, when a leaf Na level of 0.5% was associated with a reduction of 18% in predicted yield (Fig. 3).

Evapotranspiration and leaching fraction

Leaching fraction was significantly higher in the salinised treatments: on average, it was 24% in control trees and around 51% in trees receiving Tr2 and Tr3 (Table 2). This reflected significantly lower evapotranspiration in the salinised plots (Table 1). Overall average annual evapotranspiration was 993 mm in the control plots and 648 mm in plots receiving Tr3.

Leaching fraction and evapotranspiration were not significantly affected by tree spacing, nor were any interactions significant.

Discussion

Responses of EC_e and foliar Na, Cl, and nutrients to irrigation-water salinity

Soil salinity responded more quickly to salinity in irrigation water than did leaf Na and Cl levels. The increase in soil salinity occurred within 1 year of application, and there were seasonal fluctuations but no consistent increase after this and there were few EC_e values greater than 3 dS/m. We attribute this to high leaching fractions in the wetted zone, especially at the higher salt treatments (see below). By contrast, leaf Na and Cl continued to increase for 5–7 years. The pattern of increase was particularly striking for leaf Na, which was low for all treatments until the fourth year, during which it increased 3-fold in the highest treatment, then remained fairly stable (Fig. 1). This is remarkably consistent with other studies that show that Na progressively accumulates in the wood, until the fourth season, when it suddenly begins increasing in the leaves (Bingham *et al.* 1974; Cerdá *et al.* 1990; Dasberg *et al.* 1991). Foliar Na accumulation is limited by reabsorption of Na from the xylem stream in the root and basal stem (Storey and Walker 1998), but it appears that the capacity is eventually exceeded during long-term salinisation.

Leaf K levels were substantially lower in salinised than in the control plots, which may be explained in part by higher leaching losses due to the high leaching fractions recorded in the salinised plots. In addition, high soil Na concentrations may increase leaching losses of K (Levy and Syvertsen 2004) and also directly lower K uptake (Grattan and Grieve 1998). Current fertiliser practices use higher applications of K than used here, although rates used in this experiment were standard at the time (K. Bevington, unpublished). By contrast, leaf N, P, and Mg levels all tended to increase with salt treatment. This was probably an indirect effect of salinity, as a consequence of decreased growth of salinised trees. Our results are consistent with those of Garcia-Sanchez *et al.* (2002, 2003), who reported an increase in leaf N and a decrease in K in salinised sour orange seedlings and in grapefruit trees. By contrast, Bañuls and Primo-Millo (1992) found that N accumulation was negatively correlated with Cl uptake, and suggested some form of competition between NO_3 and Cl ions, a pattern that was not evident in our study.

Yield and growth responses to EC_e, leaf Na, and Cl

The relationships between yield or growth and EC_e, leaf Cl, and leaf Na were highly variable both within and among years, and as indicated by standard errors larger than the coefficients in most cases (Table 5). However, statistical modelling revealed underlying trends in most relationships, as indicated by models including salinity terms receiving many times more statistical support than the null models (Table 4). In this discussion we present both predicted and actual results so that readers can evaluate both. There was virtually no relationship between yield and EC_e (Fig. 4). This is probably because high leaching fractions were achieved, especially in the highest salt treatments, and soil salinity levels were low to moderate throughout the trial. The low soil salinity was probably due to a combination of factors: high leaching factions (up to 50%); highly permeable soils with low clay content; and a well managed irrigation system. Based on average EC_e levels in Year 9, our models predict a yield loss of 2.1% in the highest treatment relative to the control (Table 6). By comparison, Maas (1990) suggests that for orange trees, the yield threshold is 1.7 dS/m with a 16% yield loss for each dS/m above that, equivalent to a 19% yield loss for Tr3 based on values in Year 9. Gutteridge, Haskins, Davey (1999) took the work of Maas (1990) a step further by weighting the yield response to salinity for duration of salt treatment, and for Year 8 predicted a 64% decrease for each dS/m above 1.7 dS/m, equivalent to a 74% yield decline in our highest treatment in Year 9. As with the responses to irrigation-water salinity (Grieve *et al.* 2007), growth was affected more than yield by salinity in soil and leaves. Soil salinity in the highest treatment in Year 9 was associated with a predicted decrease in trunk-diameter growth in single-planted trees of 48%. Predicted reductions were 56% in the double-planted trees.

Table 5. Model weighted averaged coefficients and standard errors for the relationships between yield and the fixed effects EC_e, leaf Na, or leaf Cl (designated X in table below), tree spacing (single-planted or double-planted), duration of salt treatment and, for EC_e, month of sampling (4 April–8 August)

Global models were of the form: Yield ~ Spacing + X * Duration, where X is leaf Na or leaf Cl; and for EC_e: Yield ~ Month + Spacing + EC_e * Duration

X:	EC_e dS/m	s.e.	Leaf Na (%)	s.e.	Leaf Cl (%)	s.e.
Intercept	53.66	7.03	52.29	7.28	48.63	11.00
X	−0.024	0.430	−17.42	6.68	18.54	11.03
Single-planted	−3.603	1.272	−0.053	0.339	−3.073	1.292
Month	−0.002	0.064	n.a.	n.a.	n.a.	n.a.
Duration	0.054	0.350	−0.121	0.293	1.506	2.080
X * Duration	−0.063	0.036	−0.201	0.318	−5.596	1.976

n.a., Not applicable.

Table 6. Observed mean EC_e, leaf Na, and Cl levels for the lowest (Tr0) and highest (Tr3) salt treatments near the start and end of the trial, with corresponding actual and predicted yield losses associated with the Tr3 relative to Tr0 levels

Note that duration of salt treatment was a factor in predicting yield losses, and month of sampling also affected the relationship between yield and EC_e. Values in parentheses are s.e.m.

Explanatory variable	Year	Mean Tr0	Mean Tr3	Yield loss for Tr3 relative to Tr0 (%)	
				Actual	Predicted
EC_e (dS/m)	1 – Aug.	0.60 (0.07)	1.99 (0.43)	2.6 *increase*	0.2
	9 – Apr.	1.07 (0.24)	2.86 (0.47)	23.7	2.1
Leaf Na (%)	2	0.014 (0.003)	0.041 (0.007)	5.8 *increase*	0.9
	9	0.023 (0.003)	0.473 (0.021)	23.7	17.0
Leaf Cl (%)	1	0.12 (0.01)	0.18 (0.03)	2.6 *increase*	1.6 *increase*
	9	0.09 (0.02)	0.38 (0.05)	23.7	16.4

The importance of 'month' in the relationships between EC_e and salt treatment (Table 3) and yield and trunk-diameter increment (Table 4) shows that the timing of soil sampling is critical, and is potentially a major source of variation when comparing yield or growth responses among different studies. Ideally, a weighted seasonal average soil salinity would be used in estimating effects on yield, but information is lacking on the most appropriate weightings to use, and the guidelines to compare values against. Nonetheless, we conclude that the threshold soil salinity values for maximum yield suggested by Maas (1990) are conservative in relation to our findings for citrus at the experimental site.

The modelled relationships of yield and growth to leaf Na did not change with duration of treatment, but the amount of leaf Na increased markedly in the higher treatments. Thus, yield reductions increased with duration of salt treatment (Fig. 4). In Year 2, leaf Na in the highest treatment was associated with a predicted yield reduction of only 1% and a 4% reduction in trunk-diameter growth. In Year 9, leaf Na in the highest treatment relative to the control was associated with a predicted reduction of 17% in yield and 59% in diameter growth of single-planted trees. The actual reduction in yield was slightly larger, at 24% (Table 6). The constancy of the yield–leaf Na relationship suggests that either leaf Na was responsible for the yield decline, or that the responses of both to irrigation-water salinity were subject to similar lag times.

Both the amount of leaf Cl, and the adverse effects on yield and growth associated with high leaf Cl, increased with time. In Year 1, leaf Cl levels in Tr3 relative to Tr0 were associated with a predicted yield *increase* of 2% and growth decrease of 6% (Table 6, Figs 3 and 4). In Year 9, leaf Cl in Tr3 was associated with a predicted 16% yield decrease and a 41% growth decrease. The actual decrease in yield was 24%.

The leaf tissue levels of around 0.5% for both Na and Cl that were observed after prolonged exposure to high-salinity treatments have been categorised as high (for Cl) to excessive (for Na) based on visual symptoms of salt damage (Robinson 1986). The predicted yield and growth decreases associated with these tissue concentrations indicate that by the time visual symptoms of salinity are evident, there is a substantial effect on citrus productivity. While moderate increases in irrigation-water salinity were associated with small yield increases (Grieve *et al*. 2007), our data showed no evidence that small increases in leaf Cl and Na were associated with increased yields (Fig. 4). Stimulation at intermediate salinity levels, if present, would not be detected with the linear models used in our analyses, but including a quadratic term in the models resulted in a concave rather than a convex response. Regardless of the shape of the response curves, yield decreases were minor in the early years of elevated salt levels, and became a concern only after several years of exposure to the 2 highest salt treatments.

Evapotranspiration and leaching fraction

Salt treatment markedly reduced evapotranspiration, as has been demonstrated for citrus trees in response to short-term salt treatment (Li Yang *et al*. 2002). Whereas short-term effects are probably mediated through changes in stomatal conductance, in the long term, effects on total leaf area would also be important, because tree growth, canopy volumes, and average leaf size are all reduced by salinity (Syvertsen *et al*. 1988; Lloyd and Howie 1989). All plots received the same amount of water, so this reduction in evapotranspiration led to an increase in leaching fractions in salinised plots. As a result, the relationship between irrigation-water salinity and soil salinity was not linear, which helped to keep soil salinity levels moderately low in plots receiving saline irrigation water. Plants respond to the salinity of the soil solution rather than directly to irrigation-water salinity, so the effects of saline irrigation water reported here may have been greater if leaching fractions were held constant over all treatments, a factor to be considered when designing and operating salinity experiments.

The marked decreases in evapotranspiration (and by inference, tree water use) estimated here in the salinised plots were accompanied by small yield increases at moderate salinity levels and small yield decreases at the highest salinity level (Grieve *et al*. 2007). Tree water-use efficiency, expressed in terms of harvested portion of the crop produced per unit of water consumed, was therefore higher in salinised treatments. This is probably due to the higher yield efficiency in salinised trees (Grieve *et al*. 2007). We did not estimate tree dry-matter production, but salinity treatments reduced trunk-diameter growth by up to 68%, so that water-use efficiency in terms of dry-matter production was probably not increased by salt treatment.

To conclude, our analysis of leaf and soil parameters has shown that generalised models of citrus yield and growth responses to irrigation-water salinity must be qualified by the specific characteristics of the soil and irrigation practices present at the site. The widely used figures of Maas (1990) appear to be conservative in their estimated effects of salinity on citrus growing under the conditions in the experimental orchard. This suggests that when water-supply managers and policy makers use such models, they should be prepared to make judicious allowances for the conditions and practices that exist in their areas. Similarly, irrigators applying leaf and soil analysis guidelines should give more weight to long-term patterns of Na and Cl levels, rather than placing emphasis on occasional elevated readings alone.

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