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Long-term effects of saline irrigation water on growth, yield, and fruit quality of 'Valencia' orange trees

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Abstract. Citrus is regarded as a salt-sensitive crop, but its yield response to salinity is affected by variety, rootstock, duration of salt exposure, irrigation management, soil type, and climate. This study quantified the yield response of mature Valencia [*Citrus sinensis* (L. Osbeck)] orange trees on sweet orange (*C. sinensis*) rootstock to increased levels of sodium chloride in irrigation water in the Sunraysia area of the Murray Valley in south-eastern Australia. The orchard was planted on a loamy sand and trees were irrigated and fertilised with a well-managed under-tree microsprinkler system. 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. Overall yield effects were smaller than expected, and did not conform well to the often used bent-stick model. Relative to the control, yield was initially higher (by up to 9%) in the intermediate salt treatments, and 3% lower in the highest treatment. However, relative yields of salinised trees decreased with time, and in the final year of the experiment, yield of the highest salt treatment was 9% lower than the control. Yield increases in the intermediate treatments resulted from increases in fruit number. All 3 salt treatments decreased average fruit weight by 4% and decreased juice content but increased juice sugar and acid content. Salt treatment strongly reduced trunk growth, and the effect increased with time. Our results show that with appropriate irrigation management, soils, and rootstocks, citrus trees can maintain productivity at salinity levels of 2.0 dS/m or more, but fresh fruit profitability is likely to be lower because of a reduction in average fruit size.

Additional keywords: River Murray, semi-arid irrigation area, multi-model inference, salinity.

Introduction

Salinity in soil and water has numerous adverse effects on the growth and production of crop plants throughout the world (Kozlowski 1997). In south-eastern Australia, salinity levels in the Murray River are a concern (Gutteridge, Haskins, Davey 1999; MDBC 2005) and already reach levels in some areas that can negatively affect horticultural crops irrigated with river water. Irrigators and river managers need accurate information regarding the nature and magnitude of these effects in order to respond appropriately.

Citrus has been classified as 'salt-sensitive' by Maas and Hoffman (1977), who used a 'bent-stick' model to estimate yield responses of a range of crop plants to salinity and soil and irrigation water. The bent-stick model assumes a salinity threshold, below which there are no effects on yield, and a linear decline in yield above the inflection point. Maas and Hoffman (1977) based their model on short-term growth studies of citrus growing in sand culture, because at that time there had been few long-term experiments under carefully controlled field conditions. Maas (1993) updated the model to incorporate results from more recent studies (e.g. Bielorai *et al*. 1978, 1988; Levy *et al*. 1979; Francois and Clark 1980; Cerdá *et al*. 1990; Dasberg *et al*. 1991), and proposed that yield of citrus does not decrease significantly until a threshold value of 1.4 dS/m is reached in saturated soil extracts (EC_e), and then declines linearly as salinity increases above this value by 13% per dS/m. However, as pointed out by Storey and Walker (1998), this model was based on widely variable experimental data and yield response varies with duration of salinisation; in several studies, yield decline was not observed until the fourth season of salinisation (Bingham *et al*. 1974; Cerdá *et al*. 1990; Dasberg *et al*. 1991). Other studies have established the importance of rootstocks in determining salinity effects on fruit yield (Cerdá *et al*. 1990; Levy and Syvertsen 2004). There have also been reports of minor but inconsistent effects of salinity on citrus fruit quality (Maas 1993).

Clearly, accurate assessments of the effect of salinity on horticultural crop yield and quality need to account for the effect of local soil conditions, management practices, and specific scions and rootstocks. This was illustrated in a long-term study of field-grown grapevines conducted in the Sunraysia area of the Murray River (Prior *et al*. 1992), which found that the magnitude of yield losses was also strongly affected by soil texture. In addition, there was little evidence of a yield threshold, and overall yield losses were greater than predicted from the bent-stick model. Thus the general applicability of the bent-stick model to the response of perennial crops such as citrus should not be presumed without some caution.

This study was undertaken to quantify the long-term yield and fruit quality responses of field-grown Valencia orange trees to increased levels of sodium chloride in irrigation water under the

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conditions of soil and climate that are found in the Murray Valley, and to test the adequacy of the bent-stick model in describing these effects. The trial was carried out over a 9-year period, and examined growth, yield, yield components, and fruit quality for Valencia scion grafted on sweet orange (*Citrus sinensis*) rootstock growing in loamy sand soils typical of the area. The orchard was fertigated with a well-managed under-tree sprinkler system. Relationships between yield and soil and leaf salinity will be explored in a companion paper (Prior *et al.* 2007).

Materials and methods

Location

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. Wentworth, 10-km distant, receives 286 mm mean annual rainfall that is, on average, evenly distributed through the year. Summers are hot and winters cool; mean monthly maximum and minimum temperatures for January are 32.9 and 17.1°C, and for July are 15.6 and 4.9°C, respectively (Bureau of Meteorology 2006). The soil was a Tiltao sand (Northcote and Boehm 1949) (Uc5.12; Northcote 1979) with a structureless, calcareous A horizon to 1.0–1.2 m and a sandy loam B horizon.

Experimental design and treatments

The experimental orchard was planted in 1960 and consisted of 34 rows, each 100 m long. Valencia orange [*Citrus sinensis* (L. Osbeck)] trees on sweet orange (*C. sinensis*) rootstock were spaced at either 7.3 by 7.3 m (single-planted) or 7.3 by 3.7 m in the row (double-planted). Double-planted trees formed hedgerows running in a north–south direction. In 4 plots, alternate trees were on trifoliate orange [*Poncirus trifoliata* (L. Raf.)] rootstock, but these plots were excluded from our analyses. The orchard 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 of 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. There were 32 treatment plots arranged in two 4 × 4 Latin squares, so that each salinity treatment (described below) was represented once in each row. Thus, for each salinity treatment, there were 5 replicates of single-planted trees and 2 replicates of double-planted trees.

The 4 salinity treatments began in September 1982 and continued until the end of May 1991. The Year 1 harvest occurred at the end of 1983. The salt treatments were river water either untreated as a control (Tr0) or injected with NaCl solution (200 g/L) to give 3 additional, salinised treatments. Mean electrical conductivity of the irrigation water (EC_i) over the 9 years of the trial was 0.44 dS/m for Tr0, and 1.28 dS/m for Tr1, 1.96 dS/m for Tr2, and 2.50 dS/m for Tr3 (Table 1). 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 that of 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. 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). No boron was detected.

Table 1. Mean electrical conductivity of applied irrigation water (EC_i) each year for each treatment

Tr0 is the river-water control treatment, to which NaCl solution was injected to generate the salinised treatments

Year	Tr0	Tr1	Tr2	Tr3
1982–83	0.45	1.24	1.90	2.38
1983–84	0.37	1.12	1.69	2.21
1984–85	0.46	1.30	1.95	2.60
1985–86	0.48	1.49	2.11	2.85
1986–87	0.38	1.43	2.18	2.93
1987–88	0.48	1.27	2.20	2.43
1988–89	0.47	1.27	1.92	2.29
1989–90	0.43	1.17	1.95	2.45
1990–91	0.40	1.24	1.78	2.40
Mean	0.44	1.28	1.96	2.50

Management

The irrigation system used pressure-compensated microsprinklers spaced 3.7-m apart in the tree line, and located 1.85 m from the tree trunks, so single-spaced trees had 2 sprinklers each. These gave a continuous wetted strip 4–5 m wide (60–65% 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. Use of this irrigation system and 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 and both tree spacings were given the same total amount of water.

Major nutrients were supplied at annual rates of 158 kg/ha N (as urea and monoammonium phosphate), 38 kg/ha P (as monoammonium phosphate), and 40 kg/ha K (as potassium sulfate) over all 9 years. 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. Trees were hedged and topped to control their size in April 1982, February 1984, and March 1989.

Plant measurements

Yield and total fruit number were recorded annually for each plot. Samples of 12 fruit per plot (20 in 1991) were taken in September or October each year for assessment of % juice, juice sugar content, and total acidity. Juice sugar content was determined using a temperature-compensated refractometer, with readings corrected for acidity. Total acidity was determined by titration with 0.1 N sodium hydroxide solution using phenolphthalein indicator (Soule and Grierson 1986). In 1983, 1984, 1986, 1987, 1989, and 1991, rind thickness was also measured.

Total soluble solids (TSS) were calculated as:

$$\text{TSS (kg/t)} = \text{Juice content (\%)} * \text{Sugar content (°Brix)}/10$$

We also calculated production of TSS on a per hectare basis. Trunk circumference 150 mm above the graft union was measured annually, from which diameter increment was calculated as an index of tree growth.

Statistical analyses

Our analytical approach was to use multi-model inference based on information theory. Akaike's information criterion (AIC) for small samples was used to rank and weight the models (Burnham and Anderson 2002). The AIC is a measure of Kullback-Leibler information, a fundamental conceptual measure of the relative distance of a given model from full reality (Burnham and Anderson 2001). The AIC takes into account both the statistical goodness-of-fit and the number of parameters that have to be estimated to achieve this particular degree of fit, by imposing a penalty for increasing the number of parameters. It is defined as $-2L_m + 2K$, where L_m is the maximised log-likelihood and K is the number of parameters in the model. The small sample version is the AIC_c, which should be used when $n/K < 40$; it includes the correction factor $[2K(K + 1)]/(n - K - 1)$, where n is the number of observations (Burnham and Anderson 2001). Such information theoretic methods provide a more rational approach to model selection than do the traditional frequentist methods, and avoid the arbitrary dichotomies used by null hypothesis testing (Burnham and Anderson 2001). In addition, we used model averaging because designation of a single 'best' model is often unsatisfactory when there are several closely related models, and model averaging can provide a more stable and less biased estimate of effect size than any single best model (Burnham and Anderson 2002). All 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, tree spacing, and some possible interactions. In addition, we needed to consider that effects of salt may change with duration of salt treatment, so some models included the term 'duration plus duration by salt treatment'. Salt treatment was treated as a categorical factor because a preliminary scatter-plot showed that the yield response to it was non-linear, and it did not conform to any standard function. Spacing was also a categorical factor, but duration of salt was a continuous one. A common candidate model set, shown in Table 2, was used for the following response variables: yield, fruit number, mean fruit weight, juice content, sugar content, acidity, TSS and TSS per hectare, and annual trunk-diameter increment. Square-root transformation was required to normalise trunk-diameter data, but no transformation was required for the other attributes. It was necessary to use mixed-effects models to account for the non-independent repeated-measures of each attribute. Thus 'year' was a random effect that accounted for stochastic temporal variation, while 'duration' incorporated trends with time. Maximum likelihood estimation was used because these models had different fixed effects structures (Crawley 2002). Possible spatial correlations were accounted for using a linear correlation argument (form = rows + columns) in the models. In practice, spatial effects were minimal, barely extending into adjacent plots along rows, and not across rows because the range of influence was 3–4 row spacings and plot centres were 4 row spacings apart. For each variable, we used the weighted average coefficients of all models receiving ≥10% of the AIC_c weight (Table 2) to estimate the magnitude of effects of salt, spacing, and duration of salt treatment.

Our analyses showed an approximately linear increase in yield with salinity of applied water for the 2 intermediate salt treatments, so we did an additional analysis excluding the data for the highest treatment. The models in this analysis were the same as for the previous analysis, except that they used actual salinity (electrical conductivity) of the irrigation water in each year as a continuous variable, rather than salt treatment as a categorical one.

Results

Leaf Na and Cl levels

Leaf salinity levels are presented in detail by Prior *et al.* (2007), and are briefly summarised here to provide context for the

Table 2. Fixed effects of each of the 8 models in the candidate model set and AIC_c weights for the most strongly supported models for each attribute

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 AIC_c weights for each attribute sum to 1, but for clarity, only AIC_c weights for models receiving ≥10% support, and for the null model (italicised), are shown. The operator '*' indicates main effects and interactions

Model	Yield	Fruit no.	Fruit wt	Juice content	Sugar	Acid	Rind thickness	TSS (per t)	TSS (per ha)	Trunk diam. increment
1. Spacing * salt + salt * duration				0.395		0.540		0.223		0.181
2. Spacing + salt * duration	0.221			0.112		0.109		0.270	0.218	0.464
3. Spacing * salt					0.462	0.294		0.238		0.106
4. Spacing + salt	0.466	0.474	0.270		0.500			0.256		0.249
5. Spacing							0.283			
6. Salt * duration				0.331					0.641	
7. Salt	0.160	0.344	0.603							
8. Null	*0.0004*	*0.006*	*0.052*	*0.090*	3.5×10^{-13}	2.6×10^{-11}	0.661	3×10^{-6}	1×10^{-4}	3×10^{-25}

yield effects. Leaf Na (0.01–0.02%) and Cl (0.09–0.12%) levels were low throughout the trial in the river-water treatment, but increased with EC_i and increased with time in the salinised treatments. In Tr3, leaf Cl levels were 0.18% in Year 1, and increased to 0.38% in Year 9, while leaf Na levels increased from 0.04% in Year 1 to 0.47% in Year 9.

Trunk-diameter increment

Salt treatment strongly reduced trunk-diameter increment, and the effect increased with time, especially for the higher salt treatments (Fig. 1*a*). Relative to the control, modelled diameter increment for Tr3 was 43% lower in Year 1 and 73% lower in Year 9. Diameter increment was substantially greater for single-planted than for double-planted trees.

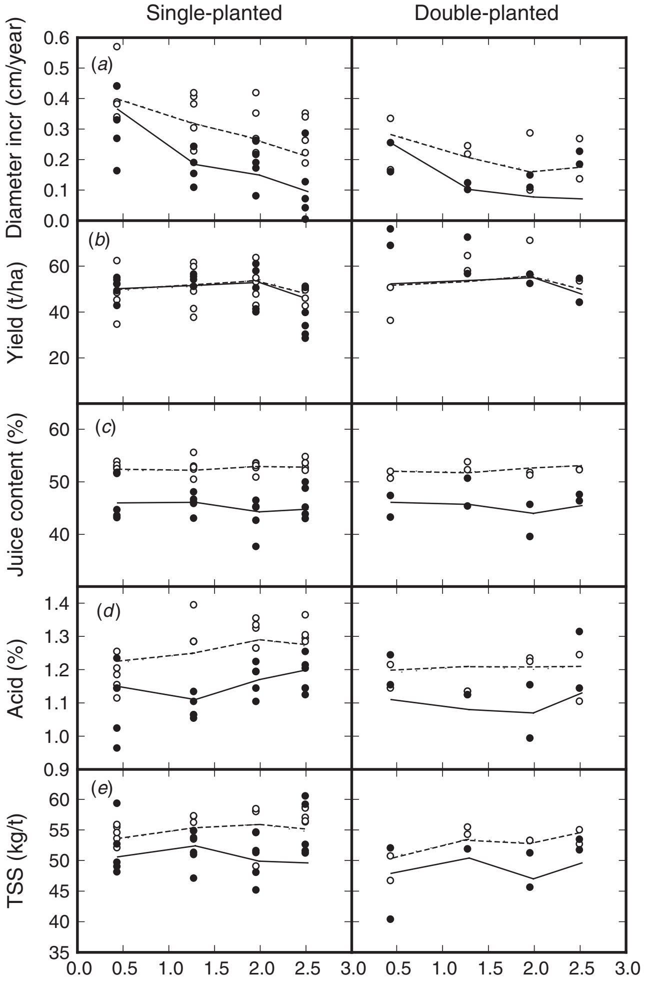

Fig. 1. Modelled effect of irrigation water salinity (EC) on attributes for which both duration of salt treatment and spacing were important: (*a*) trunk-diameter increment, (*b*) yield, (*c*) juice content, (*d*) acid content, (*e*) total soluble solids (TSS). For clarity, only Year 1 (dashed line) and Year 9 are shown, with other years intermediate. Observed plot means, corrected for stochastic effects of year (random effects), are indicated by open circles (Year 1) and closed circles (Year 9). Graphs on the left show single-planted plots, and those on the right, double-planted plots.

Yield and yield components

Salt treatment affected yield, with the factor 'salt' featuring in all the strongly supported models (Table 2; Accessory Publication). Values of coefficients for the 3 most strongly supported models for yield are shown in Table 3. Standard errors were generally higher when models contained more parameters (Table 3). Weighted averaged coefficients for these 3 models indicated that yield increased with moderate salt additions, especially in Tr2, but decreased slightly in the highest salt treatment (Fig. 1*b*, Table 3; Accessory Publication). The 95% confidence intervals of the coefficient for Tr2 (± 2 s.e.) did not include zero in any of these models, but those for Tr1 and Tr3 did include zero. Relative to the control, yields in the 2 highest salt treatments decreased slightly with duration of salinisation: for Tr2, the 9% yield stimulation in Year 1 dropped to a 5% stimulation in Year 9, and for Tr3, the decrease in Year 1 was 3% compared with 9% in Year 9. The 95% confidence interval for the interaction of salt Tr3 × duration of salt in Model 2 did not include zero, indicating a progressive decline in yield with time in this treatment (Table 3). On average, yield was higher in double-planted than in single-planted plots, as was yield efficiency (i.e. yield/growth ratio). There was no evidence of a salt × spacing interaction.

When the analysis was repeated using irrigation-water salinity as a continuous variable, and excluding Tr3, the most strongly supported models were those with yield as a function of salinity (in dS/m) (AIC wt = 0.27) and as a function of salinity and spacing (AIC wt = 0.25). For both these models, the coefficient ± s.e. of the salinity term was 2.4 ± 1.1, demonstrating higher yields at the intermediate salt levels.

Salt effects on yield were partly caused by effects on fruit number. Salt treatment increased fruit number in Tr1 and Tr2 by 7 and 12%, respectively, but did not affect fruit number in Tr3 (Fig. 2*a*). The magnitude of these effects did not change with time, and there was little effect of spacing treatment on

Table 3. AIC_c weights and coefficients of the 3 most strongly supported models used to estimate yield

The full candidate set of models is shown in Table 2. Values of coefficients derived from these models are presented, and associated standard errors are shown in parentheses. None of the 3 top models included the spacing × salt interaction, so these coefficients are not listed. The intercept indicates the yield for double-planted trees receiving salt Tr0 in Year 0. Spacing SP refers to single-planted trees, and Duration is duration of salt treatment in years. Salt treatment was treated as a categorical variable, with Tr0 the river-water control

	Model 4	Model 2	Model 7
AIC_c weight	0.466	0.221	0.160
Intercept	52.25 (5.96)	50.08 (12.96)	50.36 (5.88)
Spacing SP	–2.63 (1.28)	–2.64 (1.28)	
Salt Tr1	1.65 (1.63)	2.87 (3.53)	1.64 (1.64)
Salt Tr2	3.70 (1.58)	8.74 (3.39)	3.70 (1.60)
Salt Tr3	–3.11 (1.62)	3.90 (3.50)	–3.13 (1.63)
Duration		0.43 (2.30)	
Salt Tr1 × Duration		–0.24 (0.63)	
Salt Tr2 × Duration		–1.01 (0.60)	
Salt Tr3 × Duration		–1.39 (0.62)	

fruit number. All 3 salt treatments decreased mean fruit weight by ~4%, irrespective of spacing or duration of salinisation (Fig. 2*b*).

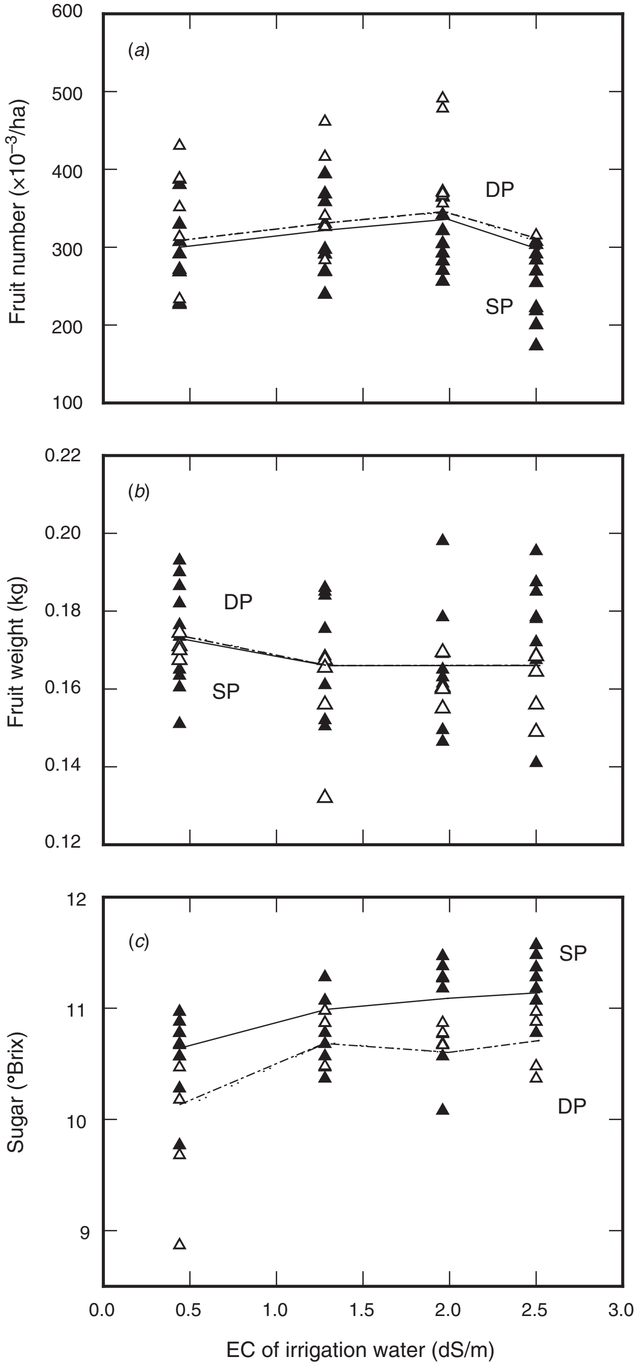

Fig. 2. Modelled effect of irrigation water salinity (EC) on attributes for which tree spacing was important: (*a*) fruit number, (*b*) mean individual fruit weight, and (*c*) juice sugar content. SP indicates single-planted trees (solid line), and DP, double-planted trees (dot-dashed line). Plot means, corrected for stochastic effects of year, are indicated by closed triangles (single-planted plots) and open triangles (double-planted plots).

Fruit quality

Salt treatment had little effect on juice content in Year 1, but by Year 9, Tr2 and Tr3 both reduced juice content by ~3% relative to the control (Fig. 1*c*). Juice content decreased in all treatments during the trial. The effect of tree spacing on juice content was very small, although spacing was a factor in 2 strongly supported models.

The 3 salt treatments all increased juice sugar content; this effect was slightly smaller for Tr1 (3.4%) than for Tr2 (4.4%) and Tr3 (4.8%) (Fig. 2*c*). There was little evidence that this effect changed with duration of salinisation, with this term absent from strongly supported models (Table 2). There were no effects of either salt or spacing on rind thickness (data not presented), as indicated by the null model receiving the greatest support (Table 2).

Sugar content was higher in fruit from single-planted than from double-planted trees (Fig. 2*c*).

Acid content was slightly higher in Tr2 and Tr3 than in the control (Fig. 1*d*). Acid was uniformly lower in Year 9 than in Year 1, and lower in fruit from double-planted than from single-planted trees.

Total soluble solids were initially higher in fruit from the salinised plots, but by Year 9, they were lower in Tr2 and Tr3 than in the control (Fig. 1*e*). They were higher in fruit from single-planted than from double-planted plots, and decreased with time in all treatments. Similarly, on a per hectare basis, TSS were considerably higher in fruit from the salinised plots, but by Year 9, they were 14% lower in Tr3 than in the control (Fig. 3). Total soluble solids per hectare decreased with time for all treatments, especially Tr2 and Tr3. There was no difference between single-planted and double-planted plots.

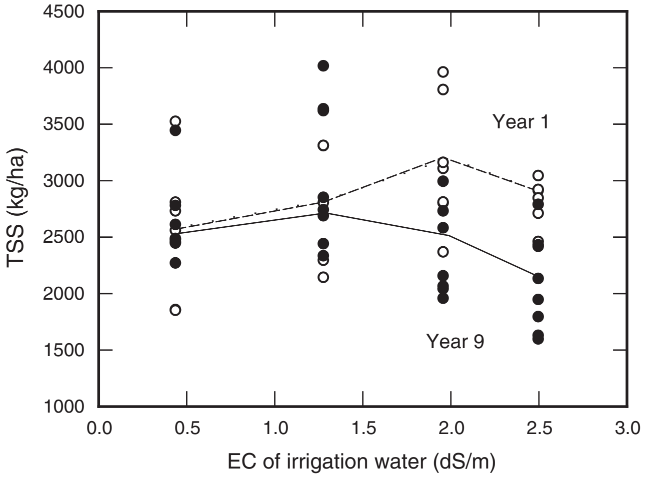

Fig. 3. Modelled effect of irrigation-water salinity (EC) on total soluble solids (TSS) per hectare, the attribute for which duration of salt treatment was important. For clarity, only Year 1 (dashed line) and Year 9 are shown, with other years intermediate. Actual plot means in Year 1 (open circles) and Year 9 (closed circles) are also shown, corrected for model weighted averaged stochastic effects of year (i.e. random effects).

Discussion

Evidence for the strong effects of salinity on citrus tree physiology is provided by the decrease in tree growth as indicated by trunk-diameter increments. These increments were reduced by salinity from the outset, and the effect became more severe as the trial progressed. Adverse effects of salinity on growth of citrus have been frequently reported in the literature (Maas 1993) and may be caused either by the accumulation of specific 'toxic' ions such as chloride or sodium, or by osmotic effects, or both. The effect of salinity on trunk growth was proportional to the conductivity of the irrigation water, and after 9 years, growth had almost ceased in the highest salinity treatment plots.

Despite the marked reduction in trunk growth, the effects of salt on yield were less pronounced and more complex than for many other crops. In most trials, crop yields are unaffected by increasing salt up to a threshold level, after which yield declines in a linear fashion [i.e. the 'bent stick' model of Maas and Hoffman (1977)]. In our trial, with only 4 levels of applied salinity, it was not possible to fit a complex response function to the yield data. However, the application of moderate levels of salinity (Tr1 and Tr2) actually increased overall yields, and this effect was maintained throughout the length of the trial. Only at the highest level of salinity (Tr3) was yield reduced, and then only slightly. Our results contrast with those of others (Bingham *et al.* 1974; Cerdá *et al.* 1990; Dasberg *et al.* 1991; García-Sanchez *et al.* 2003) in which yield of citrus trees declined after 2–4 years of salt treatment. This slight overall effect of salinity on yield may be attributable, at least in part, to the uniformity of distribution of the irrigation system, the absence of foliar wetting due to the use of an under-tree spray system, and the careful irrigation scheduling followed, which had been shown previously to increase citrus yields in the trial orchard (Grieve 1989). The deep sandy soil in the orchard also permitted good leaching and limited the accumulation of salt in the soil profile (Prior *et al.* 2007). Another factor may be the capacity of the sweet orange rootstock to tolerate elevated levels of salinity, as previously reported for seedlings (Grieve and Walker 1983).

The effects of salinity on fruit weight and fruit number were quite different. Whereas fruit weight was reduced at all levels of salinity, fruit numbers increased at moderate salinity levels, falling to values comparable with the control at the highest levels. The smaller fruit size possibly reflects a combination of different effects of salinity: at lower levels a reduction in the amount of assimilates individually available to the greater fruit numbers present, and at high salinity a decrease in the total amount of assimilates available. Fruit size is also reduced by low leaf potassium levels (Chapman 1968), which were observed to decrease in this trial (Prior *et al.* 2007). However, reduction in leaf potassium levels did not become pronounced until after Year 6, whereas fruit size was affected from the outset. Current fertiliser practices in the area use higher applications of potassium than those current at the time of the experiment, which were used in this trial (K. Bevington, unpublished). Increased fruit numbers at moderate salinity levels may be due to increased flowering, as has been suggested by Levy and Syvertsen (2004); moderate salinity may have acted as a stressor similar to drought or winter cold, which can cause increases in flowering. However, the effects we found on fruit yield components differ from other reports, which have generally shown that fruit numbers decrease due to salt stress, without significant changes in fruit weight (Maas 1993). For example, Howie and Lloyd (1989) found that salinity levels similar to our Tr2 decreased flowering and fruit set. In our trial, the increase in fruit numbers more than compensated for the reduced fruit weight, but given that there is little demand for small fruit in the fresh fruit market, it is likely that orchard profitability was reduced by salinity.

Sugar levels were higher in juice from fruit from salinised trees, and this effect was maintained throughout the trial, together with smaller and more variable effects on acid levels. These changes initially led to elevated TSS levels in fruit from salinised trees but the yield of TSS per hectare fell over time. This was due to a combination of effects of salinity on fruit yield and percent juice levels, which resulted in similar reductions in TSS yield to reduction in total fruit weight at the highest salinity levels. At the lowest level of increased salinity, TSS yields were increased consistently throughout the trial. These increases in sugar, acid, and TSS are similar to those reported for 'Shamouti' oranges (Bielorai *et al.* 1988), grapefruit (Levy *et al.* 1979), and lemons (Nieves *et al.* 1991), although Francois and Clark (1980) found no effect in Valencia orange.

The overall effects of increased salinity in irrigation water in this trial were a slight reduction in yield in the highest salt treatment, but increased yield at moderate salinity levels. These effects were associated with a sustained and significant reduction in tree growth, so that yield efficiency was therefore higher in salinised than in control trees. The increases in yields at moderate salinity levels were also accompanied by decreases of up to 35% in estimates of evapotranspiration (Prior *et al.* 2007), and hence greater water-use efficiency. It is important to note, however, that increased yields were at the expense of average fruit size. Although the stimulatory effects of moderate salinity levels on citrus yields were maintained throughout the 9 years of the trial, the reduced fruit size would most likely offset any perceived yield benefit. In producing fruit for the fresh fruit market, any reduction in fruit size would be a concern, as would be the reduction, in the highest salt treatment, of TSS yield in fruit grown for the processed juice market (Fig. 3). Notwithstanding the effects on quality, the trial results indicate that provided good irrigation techniques and suitable sites are used, citrus orchards planted to tolerant rootstocks will tolerate greater levels of salinity in irrigation water than was previously thought. They also suggest that the Maas and Hoffman (1977) bent-stick model is not always the most appropriate to use to assess yield decreases due to salinity.

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