Seminario: Manejo del riego y suelo en el cultivo del palto. 27-28 de Septiembre de 2006. 14 pages.
Gobierno de Chile. Ministerio de Agricultura. Instituto de Investigaciones Agropecuarias (INIA). El Centro Regional de Investigación (CRI) La Platina.

Effects of salinity and applied water on yields of 'Hass' avocado on Mexican seedling rootstock.

J.D. Oster[1] and M.L. Arpaia[2]

[1] CE Soil and Water Specialist (Emeritus), Dept. of Environmental Sciences, Univ. of California, Riverside, CA. email address: James.oster@ucr.edu

[2] CE Subtropical Horticulturist. Dept. of Botany and Plant Sciences, Univ. of California, Riverside, CA.

Abstract

A field experiment in a commercial orchard of mature 'Hass' avocados on Mexican seedling rootstock (*Persea americana*) was conducted between 1992 and 1997 to determine how yield was influenced by the amount of irrigation water applied and the frequency of application. Three amounts of applied water (targeted at 90, 110 and 130 % of estimated crop evapotranspiration) were applied at three frequencies (one, twice and seven times per week). The electrical conductivity and chloride concentration of the irrigation water, corrected for rain, were 0.7 $dS \cdot m^{-1}$ and 1.8 $mmol \cdot L^{-1}$ (65 $mg \cdot L^{-1}$), respectively. Irrigation treatment did not influence the average salinity in the rootzone, leaching fraction, and chloride concentrations in leaves. A maximum soil water salinity of about 4 $dS \cdot m^{-1}$ occurred in the lower portion of the rootzone for all irrigation treatments. Trees irrigated seven times per week had lower yields than those that received less frequent irrigation. Yields increased with increasing amounts of applied water during the last two years of the experiment. The influence of the amount of applied water and soil salinity on avocado yields and leaching fractions for treatments irrigated once and twice a week was explained using production function concepts. The threshold salinity above which yield decline occurred was determined to be 0.57 $dS \cdot m^{-1}$ and yield declined by 65% per unit of salinity above the threshold. Our results suggest that maximum yields of 'Hass' avocado on Mexican seedling rootstock are not achievable when the average annual salinity of irrigation water, including rainfall, is greater than about 0.5 $dS \cdot m^{-1}$.

Introduction

Drip irrigation for avocados (Persea americana Mill.) was first experimentally introduced into California from Israel in the late 1960's (Gustafson, 1976). In the early 1970's Gustafson et al. (1979) compared drip irrigation of 'Hass' avocado on Mexican seedling rootstock to the then standard fixed sprinkler irrigation method in a plot located in San Diego county, CA when irrigated with an irrigation water with an electrical conductivity (ECiw) of 1.1 dS/m. This study was prompted by the rising cost, and limited supplies of irrigation water in southern California. Its success contributed to the rapid expansion of the California avocado industry in the late 1970's and early 1980's.

This work was followed by a study by Meyer et al. (1992) in which the amount of irrigation applied was based on daily reference evapotranspiration data (ETo) obtained by the California Irrigation Management System (CIMIS). They found increasing yield and tree growth with increasing amounts of applied water, similar to previous research (Kalmar and Lahav, 1977; Richards et al. 1958, 1962). The Meyer et al (1992) project was followed up by the study described in this paper, which initially aimed to examine the relationship between irrigation amount and frequency on yield and tree growth of ‘Hass’ avocado on Mexican seedling rootstock where the irrigation water salinity (ECiw) was about 1 $dS{\cdot}m^{-1}$ and Cl concentration ranged from 2.3 to 3.6 $mmol{\cdot}L^{-1}$. We found that yield increased with increasing amounts of applied water with an ECiw of about 1.0 $dS{\cdot}m^{-1}$, and that soil salinity was not influenced by the amount of applied water, similar to what had been reported (Kalmar and Lahav, 1977; Richards et al. 1958, 1962) in studies were some of the treatments included purposeful underirrigation.

In the studies conducted by Kalmar and Lahav (1977) and Richards et al. (1958, 1962), ECiw ranged from 0.5 to 0.8 $dS{\cdot}m^{-1}$ and Cl concentration ranged from 1.1 to 1.3 $mmol{\cdot}L^{-1}$ (40 to 50 $mg{\cdot}L^{-1}$). The average electrical conductivity of saturated paste extracts (ECe) in the upper 110 cm of soil, where about 95% of the water uptake occurred, ranged from 1.5 to 2.5 $dS{\cdot}m^{-1}$, a surprising result since one would have expected higher salinity in treatments receiving the least amount of applied water. Consequently these salinity levels could reflect the maximum salinities (Bernstein and Francois, 1973; Shalhevet, 1994) that Mexican seedling rootstocks can generate as a consequence of water uptake. If an ECe of about 2 $dS{\cdot}m^{-1}$ in the rootzone is the maximum that can occur, ‘Hass’ avocado on Mexican seedling rootstock is extremely salt sensitive. These observations suggest that both the amount of applied water and soil salinity in the rootzone, at unusually low levels, can limit avocado yields.

The combined influence of applied water and rootzone salinity on crop yields are the foci of crop-water production functions developed in the 1980s (Letey et al., 1985; Letey and Dinar, 1986; Solomon, 1985). The production function “combines three relationships: yield and evapotranspiration, yield and average root zone salinity, and average root zone salinity and leaching fraction (Letey et al., 1985).” This production function has five coefficients: AWt, AWm, Ym, Sd, and ECt. When the electrical conductivity of the irrigation water (ECiw) equals zero (i.e. nonsaline), yields are assumed to increase linearly between a threshold amount of applied water (AWt) and an amount (AWm) that results in maximum yield (Ym). Another basic premise of the production function model is that for a given amount of applied water, if the ECiw is greater than zero, a reduction in yield caused by salinity will reduce the amount of water used by the crop, resulting in more leaching than would have occurred if ECiw equaled zero. Mass and Hoffman (1977) reported that crop yields generally are not affected by rootzone salinity until they reach a threshold value (ECt) and then decline linearly with increasing average root zone salinity (Sd; % decline per $dS{\cdot}m^{-1}$). These coefficients are an integral part of the production function model. Because this model accounts for the influence of both amount of applied water and rootzone salinity on crop water use and crop yield, it was used to evaluate the results we obtained.

Methods

Location and experimental layout. The field experiment was conducted between 1992 and 1997 in a 10-ha commercial orchard of mature ‘Hass’ avocados on Mexican seedling rootstock (*Persea americana*). The experimental site (Fig. 1) was located approximately 20-km north of Escondido, Calif at Covey Lane. The site had a southern exposure with an average slope of 16% with a standard deviation of 6%. The soil was Cieneba coarse sandy loam (pH 6) classified as a thermic, shallow Typic Xerorthents. An evaporation pan and rain gauge were located in an open area along the south side of the project area.

Figure 1: *Photo of Covey Lane taken in 2000 or 2001.*

During the experiment, climate at the site had the following average characteristics: potential evapotranspiration, 1390 mm/year; rainfall, 464 mm/year; wind speed,1.7 $m \cdot s^{-1}$; minimum relative humidity, 42%, and average relative humidity, 63%. August was the hottest month with an average daytime temperature of 24 $^{\circ}C$. December was the coldest month with an average daytime temperature of 13 $^{\circ}C$.

The grove was divided into six blocks with each block having one replicate of all combinations of applied water and irrigation frequency. The trees used to determine yields in each replicate, the record tree, were surrounded by border trees that were irrigated the same as the record tree. All record trees were topped to approximately 5.4 m and whitewashed to prevent sunburning in late July 1992. The objective was to increase the tree uniformity among the record trees and to prevent limb breakage. The other 8-m-tall border trees were not topped but were irrigated in the same manner as the record tree. Soil and soil-water samples were taken beneath the canopy of the record trees.

Water management. The Valley Center Municipal Water District supplied the irrigation water, a blend of well water and Colorado River water. ECiw ranged from 0.7 to 1.1 $dS \cdot m^{-1}$; Cl concentration ranged from 2.3 to 3.1$mmol \cdot L^{-1}$; and the average HCO_3, SO_4, Ca, Mg, and Na concentrations were 2.7, 2.4, 1.5, 1.1, and 4.1 $mmol \cdot L^{-1}$, respectively. Rain accounted for about 30 % of the total amount of applied water, which reduced the average electrical conductivity ($ECiw^*$) to 0.7 $dS \cdot m^{-1}$ and the chloride concentration to 1.7 $mmol \cdot L^{-1}$ (60 mg/L). Water was applied with under-tree microsprinklers located about 1 m from the tree trunk. A single mainline, with foot values, served each combination of applied water and irrigation frequency in all blocks. A 12-station controller, water meters, and valves were used to control the amount of irrigation water applied. Nine irrigation treatments consisted of three amounts of applied water per week with each amount applied at three frequencies: once (F1), twice (F2) and seven (F7) times per week. The targeted irrigation amounts were 0.9 (AW1), 1.1 (AW2) and 1.3 (AW3) times the estimated crop water requirement based on the pan evaporation measured on-site and assumed crop coefficient (Arpaia, 1993). Irrigation scheduling occurred weekly, usually on

Mondays. The cumulative evaporation (ETpan) of the previous was used to determine irrigation for the following week to recharge the water removed from the soil during the previous week.

The amount of water (AW) to apply was calculated using the following equation:

$$AW\ (mm) = (Kc)(ETpan)(Tw)(1.06) \qquad \text{Eq. [1]}$$

where Kc is the crop coefficient that varied during the year as follows: January.= 0.4; December, and February = 0.5; November, October, March, April, and September = 0.55; May and August = 0.60; June and July = 0.65 (Arpaia et al., 1993). Tw represents irrigation treatment with values of 0.9, 1.1, and 1.3 for the three irrigation treatments. The factor of 1.06 accounts for the variation of the discharge rate among the sprinklers and assured that water applied to 84% of the record trees equaled, or exceeded, the targeted amount. Eq. [1] did not include a pan coefficient (Allen et al., 1998) because ETpan was the same as the potential evaporation (ETo) measured at a nearby CIMIS station. No correction for runoff was made in Eq. [1] since none was observed at any time during the experiment.

AW was corrected for rainfall. Where rainfall from the previous week exceeded the calculated AW for the following week, no irrigation occurred. The rain correction was carried forward for only 30 d: the remaining excess of rainfall at the end of a month was not subtracted from calculated AW for the following month.

<u>Monitoring of soil-water salinity (ECsw) and matric potential.</u> To obtain samples of the soil water, ceramic extractors were installed 0.9 m from both the sprinkler and tree trunk at the 30- and 60-cm depths in blocks 2 through 5 in Aug. 1993, and also at the 120-cm depth in block 4 in Feb. 1994. Soil-water samples were collected whenever soil-water matric potentials were greater than about –40 kPa. Only a few samples were obtained July through November because of low water potentials. The number of samples obtained for the 30-, 60- and 120-cm depths were 779, 797, and 221, respectively.

Soil samples were taken in November and May along a 0.9-m circumference around the sprinkler each year and the saturation extracts (U. S. Salinity Laboratory Staff, 1954) were analyzed for pH, ECe, Na, and Cl. The sampling depths were 0 - 15, 15 - 30, 30 -60 and 60 - 120 cm. The distance of 0.9 m from the sprinkler was where the spatial distribution of the application rates equaled the average application rate.

In July 1994, transducer-equipped tensiometers were installed 0.9 m from the microsprinkler and the tree trunk beneath the record trees. They were installed in blocks 2 through 5 at the 0.3-m depth for treatments AW1F2, AW2 (F1, F2 and F7) and AW3F2, and at 0.15 and 0.6-m depths for treatment AW2F2. Predawn measurements of the soil-water matric potential were recorded daily on a data logger.

<u>Monitoring of tree growth chemical composition of leaves and crop yields.</u> Tree growth was monitored annually by measuring trunk circumference 20 cm above the bud union, canopy area and tree height. Five leaves per quadrant, or 20 leaves per tree, were sampled in Sept.1993 through 1996 and analyzed for the major and minor elements according to established guidelines and procedures (Embleton et al., 1960). The leaves were analyzed for N, P, K, S, Ca, Mg, Na, Cl, B, Zn, Mn, Fe, and Cu. Fruit harvesting of the record trees occurred between March and May each year. All the fruit were removed in one day, weighed and counted. To assure accuracy, only the record trees were harvested on this day.

<u>Production Function Analysis.</u> Estimates of the production function coefficients were obtained (J. McGrath, personal communication) by using the Generalized Reduced Gradient Algorithm for optimizing nonlinear problems provided by Microsoft Excel Solver plug-in (Microsoft Excel 2000, Version 9.0.4402 SR-1, Microsoft Inc., Redmond, Wash.) in combination with the ZBRENT (Press et al., 1996) root finder. The algorithm changes AWt, AWm, Ym, ECt and Sd until the minimum sum of the squares is obtained for the difference

between predicted and measured crop yields, and between predicted and measured leaching fraction.

Statistical analysis. Statistical analysis of the data was done using the General Linear Model (Minitab Statistical Software, release 13.1,Minitab Inc., State College, Pa). The Tukey method was used for pairwise comparisons among means with probabilities less than 0.055 considered significant.

Results and Discussion

Irrigation management. The water application targets of 0.9, 1.1 and 1.3 times estimated crop evapotranspiration (ETc) were exceeded due to an inability to fully correct for rainfall (Table 1 and Table 2). The average excess due to rain ranged from 340 to 360 mm (Table 2). The problem was that rainfall occurred during the winter months when the daily ETpan was low (2 to 4 $mm \cdot d^{-1}$). Reduction in applied irrigation water to fully account for rainfall would have required carrying the rain correction forward for 3 to 6 months.

Table 1. Class A pan evaporation (ETpan), estimated crop water requirement of Hass avocado on Mexican seedling rootstock (ETc), rainfall, and amounts of applied water for the three water treatments (AW1, AW2, and AW3) for four crop years starting in May 1993 and ending in Apr. 1997.

Crop Year	ETpan	ETc	Rain	AW1 [z]	AW2	AW3
May – Apr.	mm/yr					
1993-94	1390	790	340	690	830	1000
1994-95	1370	790	680	600	740	870
1995-96	1320	760	190	710	840	1010
1996-97	1490	870	340	770	910	1100
Average	1390	800	390	690	830	990

[z] The targeted irrigation amounts were 0.9 (AW1), 1.1 (AW2) and 1.3 (AW3) times the estimated ETc based on the pan evaporation measured on-site.

Table 2. Summary of the applied, target and components of applied water for the three targeted water treatments (AW1, AW2, and AW3) and the weighted average electrical conductivity (ECiw*) and Cl concentration (Cliw*) of the irrigation water and rain.

Irrigation Treatment	AW1 [z]	AW2	AW3
Average applied, including rainfall (mm/year)	1080	1220	1380
Average target, mm/year	720	880	1040
Excess irrigation, mm/year	360	340	340
Fraction rainfall	0.36	0.32	0.28
ECiw* corrected for rain, $dS{\cdot}m^{-1}$ [y]	0.64	0.68	0.72
Cliw* corrected for rain, $mmol{\cdot}L^{-1}$ [y]	1.7	1.8	1.9

[z] The targeted amounts of applied water were 0.9 (AW1), 1.1 (AW2) and 1.3 (AW3) times the estimated crop water requirement based on the pan evaporation measured on-site.
[y] The electrical conductivity of the irrigation water, ECiw, averaged 1.0 $dS{\cdot}m^{-1}$ and the chloride concentration, Cliw, of the irrigation water averaged 2.7 $mmol{\cdot}L^{-1}$. The corresponding values for rain are 0.0.

Rainfall had a significant effect on ECiw. The weighted-average electrical conductivity of the combined irrigation and rainfall, ECiw*, ranged from 0.69 to 0.72 compared to an ECiw of 1 $dS{\cdot}m^{-1}$ (Table 2). Similarly, the rain reduced the weighted-average Cl concentration, Cliw*, from 2.7 to 1.83 $mmol{\cdot}L^{-1}$.

Influences of irrigation management on soil-water matric potential, ECe, ECsw, and leaching fraction. The soil-water matric potential at the 30-cm depth for AW2 decreased more quickly for F7 and remained at more negative levels than for F2 and F1. This difference became evident on about 15 Apr. and lasted until about 1 Nov., a time period that includes the warmest and driest months of the year. This trend likely was the consequence of greater direct loss of water by evaporation at the soil surface in F7 than for F2 and F1. The soil surface was wetted each day in F7 as compared to every third or fourth day in F2 and only every seven days for F1.

The average ECe for the 0 – 120-cm-depth interval, from May 1994 to Nov. 1996, was affected little by irrigation treatment (Fig. 2), except in Nov. 1995, and there was no general increase in ECe during this period. The latter confirms that leaching occurred throughout the experiment: an increasing trend in ECe in the 0 – 120-cm-depth interval did not occur because salts applied in the irrigation water were continually moved downward (leached) through the rootzone to depths below.

The 1994-95 crop year had the most rainfall (Table 1) causing the large reduction in ECe between Nov. 1994 and May 1995 (Fig. 2). Nov. 1955 was the only time that there were significant differences in ECe among the AW treatments, with the general trend of increasing ECe with increasing AW. When soil salinity is low at the beginning of the irrigation season, higher water applications, which also apply higher salt quantities, lead to higher soil salinities (Shalhevet, 1994).

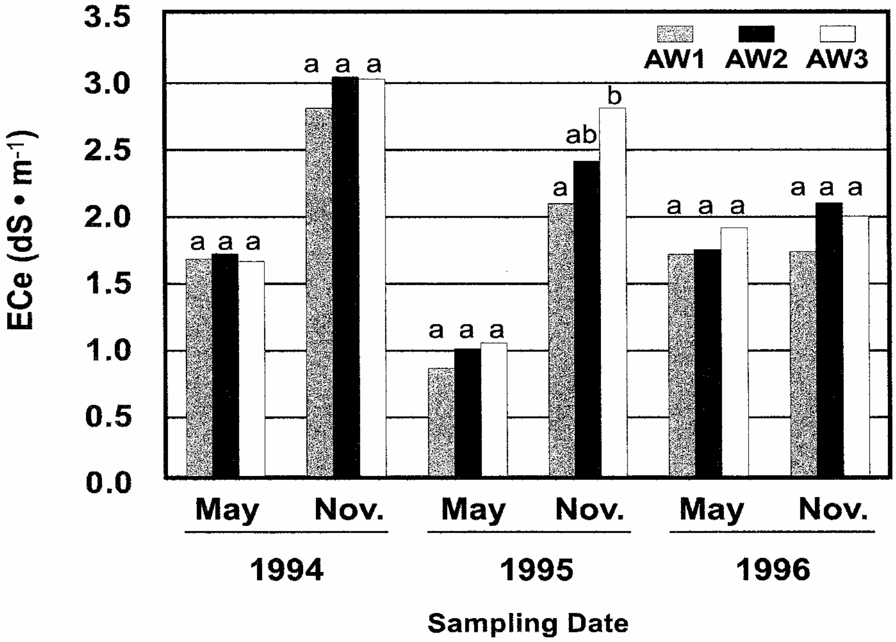

Figure 2. Influence of applied water treatment, AW, on the average electrical conductivity of saturation-paste extracts, ECe, at a soil depth of 0 – 120 cm

The interaction, AW x F, was significant (P = 0.008) because of differences among the averages in November (Fig. 3). For F1, there were no significant differences among the averages for the AW treatments. However, as irrigation frequency increased,
the greater the AW, the greater the ECe. This can be associated with two contributing factors: 1. increasing water loss by evaporation to air as irrigation frequency increases, and 2. increasing amount of applied salt as AW increases.

ECsw was influenced by depth (D), AW, crop year (CY) and interactions among these factors and with irrigation frequency for the 1994-95, 1995-96, and 1996-97 crop seasons. The effects of D and AW were small: 1. the average ECsw for the 30-, 60-, and 120-cm depths was 3.3, 3.8 and 3.6 dS/m, respectively, with only the averages for the 30- and 60-cm depths being significantly different, and 2. average ECsw for AW1, AW2, and AW3 was 3.5, 3.2 and 4.0 dS/m, respectively, with only the averages for AW2 and AW3 being significantly different.

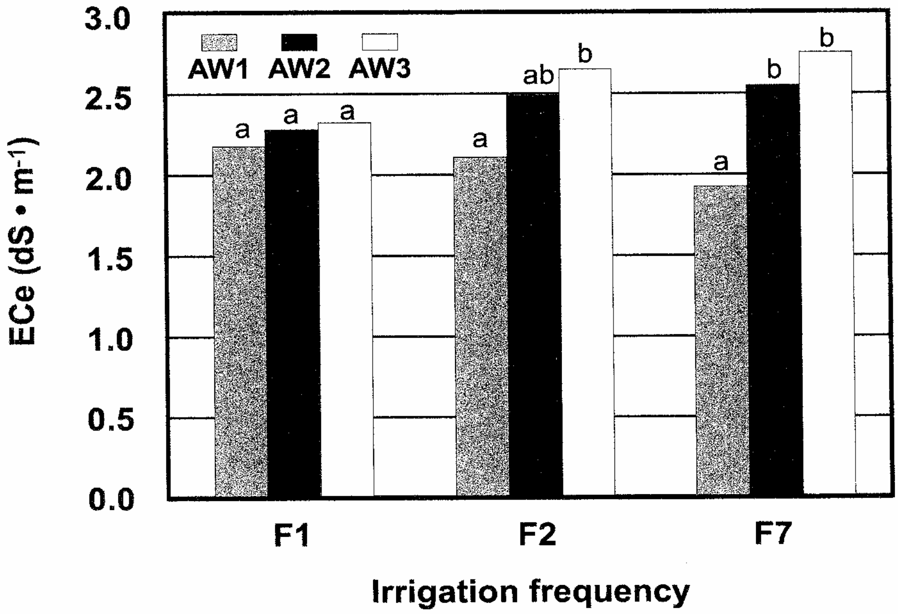

Figure 3. Applied water (AW) by irrigation frequency (F) interaction for the average electrical conductivity of saturation-paste extracts, ECe, at a soil depth of 0 – 120 cm for soil samples collected in November of each year (1993-96).

The ECsw measurements, made between December and June, reflect the wettest conditions during the experiment, when leaching was occurring at the greatest rate during the crop year. Because most or the roots in the 0 to 60-cm-depth interval were located above 15 cm (measured data not presented in this paper), we consider both the 60- and 120-cm depths to be near to, or below, the bottom of the rootzone. Consequently we assume the average ECsw of the 60- and 120-cm depths for all treatments, 3.7 $dS{\cdot}m^{-1}$, is a good estimate of the average EC of the drainage water, ECdw, for all irrigation treatments. The ratio, $ECiw^*/ECdw$, approximately equals the leaching fraction (Oster, 1984), which is defined as the ratio of the volume of drainage water divided by the volume of applied water (U.S. Salinity Laboratory Staff, 1954). Dividing 3.7 $dS{\cdot}m^{-1}$ into the ECiw* values (Table 2) results in average leaching fractions that range from 0.17 to 0.19. Considering the maximum and minimum ECsw, 5.3 and 2.5 $dS{\cdot}m^{-1}$ for the 60- and 120-cm depths, the maximum range of leaching fractions would be from 0.13 to 0.27.

The main findings of this section are that the AW treatments on ECe, ECsw and leaching fraction were small. The ECe within the rootzone averaged approximately 2 $dS{\cdot}m^{-1}$ (Fig. 2), similar to the value reported by Kalmar and Lahav (1977) and Richards et al. (1958, 1962). Apparently the ability of the trees to extract soil-water beyond an ECsw of 4 to 5 $dS{\cdot}m^{-1}$ was very limited. Our interpretations of these findings are that as applied water increased, evapotranspiration increased until the salinity of the soil-water reached a level (Bernstein and Francois, 1973; Shalhevet, 1994) that limited evapotranspiration. In other words both AW and ECsw limited evapotranspiration.

<u>Influences of irrigation management on growth, leaf composition, and yield of avocados.</u> The height of the record trees increased from 5.4 m in Feb. 1993 to 9.0 m in Dec. 1996 with all

year-to-year increases being significant. For 1992 through 1996, the average height for the AW3 treatment was significantly greater than the other two treatments. The average tree area increased from 27 m^2 in Nov. 1993 to 51 m^2 in Dec. 1996. Year-to-year increases in area were significant from 1993 to 1995; the increase between 1995 and 1996 was not significant at which time the trees within the plot were beginning to touch again. The AW3 treatment had the largest average area, 47 m^2, for 1993 through 1996, which was significantly greater than the 41 m^2 and 40 m^2 for AW2 and AW1, respectively. The effects of irrigation frequency were not significant for either growth parameter.

The trees were maintained at acceptable norms (Goodall et al., 1981) for the elements N, P, K, Mg, B, Mn, Fe, Cu and Zn. The concentrations of Na and Cl in leaf tissue obtained in Sept. 1995 and 1996 are of special interest as these are the years the yield data were obtained to assess the effects of water treatment on crop yields. The average Na concentration was 3.0 $mmol\cdot kg^{-1}$ in Sept. 1995 and 4.4 $mmol\cdot kg^{-1}$ in Sept. 1996, well below the 170 to 300 $mmol\cdot kg^{-1}$ reported to cause leaf scorch of 'Hass' on Mexican seedling rootstock (Bingham and Nelson, 1970; Mickelbart and Arpaia, 2002). The average Cl concentrations were affected by the amount of applied water (P =0.03) and irrigation frequency (P = 0.001), but not by year. The Cl concentration for AW1, 124 $mmol\cdot kg^{-1}$, was not significantly greater than 116 $mmol\cdot kg^{-1}$ for AW2, but was significantly greater than 110 $mmol\cdot kg^{-1}$ for AW3. The Cl concentration for F1, 107 $mmol\cdot kg^{-1}$, was significantly lower than for F2, 121 $mmol\cdot kg^{-1}$, and for F7, 124 $mmol\cdot kg^{-1}$. However, these are lower levels than have been reported to cause leaf damage (Mickelbart and Arpaia, 2002; Bingham et al. 1968)

The average yield of all treatments increased from 12 kg/tree in 1993-94 kg/tree to 41 kg/tree in 1995-96; however, the average yield in 1995-96, 46 kg/tree, was not significantly greater then 41 kg/tree. AW3 had the largest increase in crop yield, from 16 to 62 kg/tree, over the four crop years and AW1 had the least, from 12 to 41 kg/tree. In both cases these differences were significant.

There was a significant interaction between irrigation frequency and crop year (P = 0.022). In 1995-96, the yield for F1, 59 kg/tree, was significantly greater than in 1993-94, 11 kg/tree; for F2, the yield in 1995-96, 61 kg/tree, was significantly greater the 14 kg/tree in1993-94. For F7, there was no year when the yield was significantly greater than the 12 kg/tree in 1993-94. We believe this was the result of the limiting levels of ECsw in the rootzone occurring sooner for F7 than for F2 and F1 in a rootzone where most of the roots were in the upper 15 cm of soil. Yields for the F7 treatment were excluded from the calculations of the production function coefficients used in the Letey Production Function (Letey et al., 1985) because this function was derived for conditions where water management under field conditions is consistent with recommended practices.

The main findings of this section are that tree growth increased with increasing applied water as did crop yields. However yields did not increase through four succeeding crop seasons when irrigated daily, the F7 treatment. Both AW and F influenced Cl and Na concentrations in the leaves, but the levels were less than those reported to cause damage.

Production function. Average crop yield increased with increasing applied water for the 1995-96 and 1996-97 crop years for F1 and F2 treatments (P = 0.001). The yields were 28, 46 and 71 kg/tree for AW1, AW2, and AW3, respectively, with the yields for AW1 and AW3 being significantly different (P < 0.001), and those for AW2 and AW3 having a P < 0.08 of being significantly different. The trend of increasing crop yield with increasing applied water for the 1995-96 and 1996-97 crop years is shown in Fig. 4A.

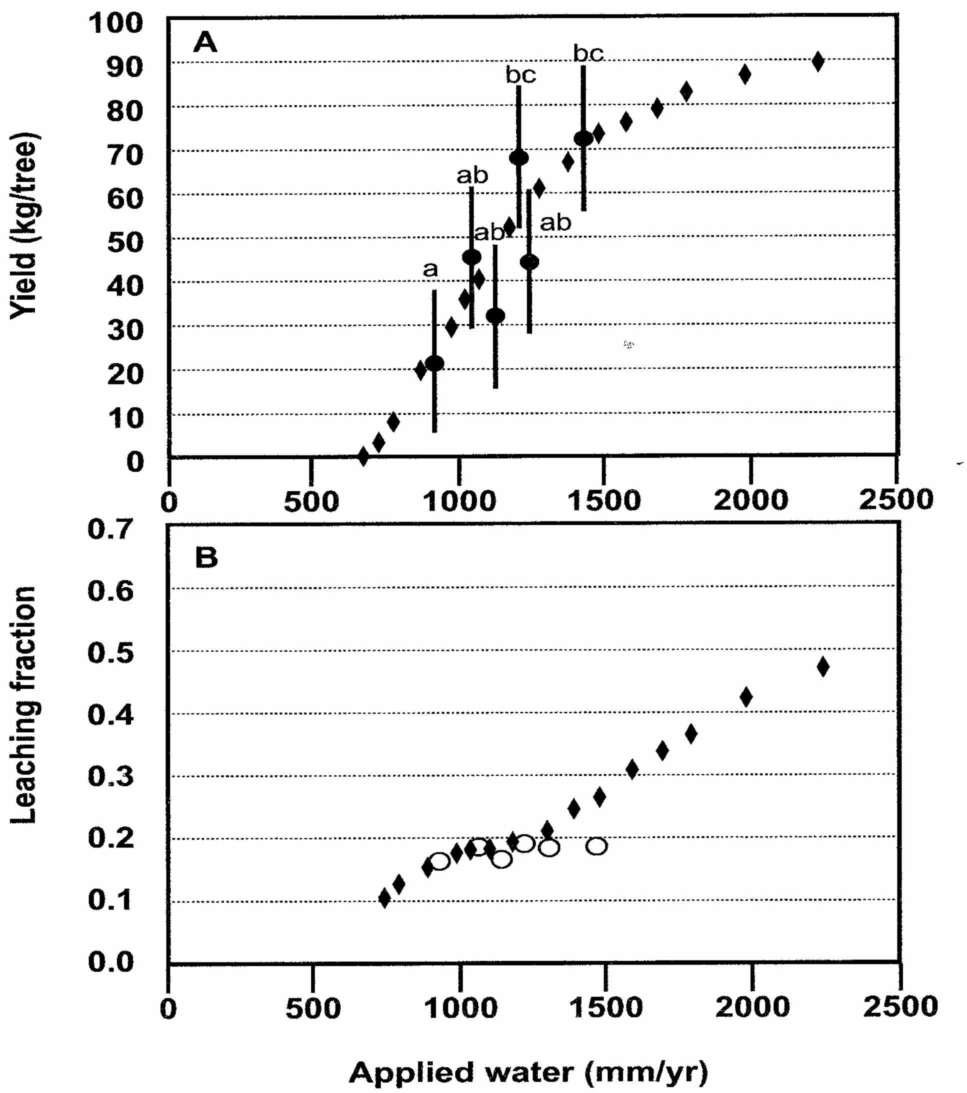

Figure 4. A. Projected and measured yield of 'Hass' avocado on Mexican seedling rootstock as influenced by the amount of applied water. Bar heights equal two times the standard error of the mean and are centered on the average yields obtained for irrigation treatments irrigated once (F1) and twice a week (F2). B. Projected and calculated leaching fractions for 'Hass' avocado on Mexican seedling rootstock as influenced by the amount of applied water. The circles represent the experimental data collected from the once (F1) and twice (F2) per week irrigation frequencies.

The yields for the two highest amounts of applied water were significantly higher than for the lowest amount of applied water. However the average leaching fraction increased little with increasing amount of applied water (Fig. 4B). The production function of Letey et al. (1985) accounted for both findings with the following production function coefficients: ECt, 0.57 $dS \cdot m^{-1}$, Sd, 63% per $dS \cdot m^{-1}$, Ym, 94 kg/tree, AWt, 620 mm/year and AWm, 1200 mm/year. These coefficients resulted in the best match between predicted and measured yields (Fig. 5A) and leaching fractions (Fig. 5B).

Using the values of 0.57 dS·m^{-1} (ECt) and 63% per dS·m^{-1} (Sd) as the Maas-Hoffman coefficients in the Mass-Hoffman equation (Maas and Hoffman, 1977),

$$Y=100 - Sd(ECe - ECt) \qquad \text{Eq. [2]}$$

where Y is relative yield, results in a Y of 0 for an ECe of 2.2 dS·m^{-1}. This corresponds to an ECsw 4.4 dS·m^{-1} (~ 2 x ECe; Letey et al., 1985). At depths of 60 and 120 cm, the only ECsw of the nine water treatments combinations that exceeded 4.4 dS·m^{-1} was the 5.3 dS·m^{-1} obtained for AW3F2. The preponderance of the ECsw data obtained at the 60- and 120-cm depths, with an average of 3.7 dS·m^{-1}, supports the conclusion that an ECsw of 3.7 dS·m^{-1} approaches a level that limits crop water uptake. The corresponding limiting value for ECe, 2.2 dS·m^{-}1, is consistent with the limiting ECe levels of 1.5 to 2.5 dS·m^{-1} obtained by Kalmar and Lahav (1977) and Richards et al. (1958, 1962).

Shalhevet has reported two sets of Maas-Hoffman coefficients for 'Hass' avocado on Mexican seedling rootstocks: Etc of 0.6 dS·m^{-1}and Sd of 80% per dS·m^{-}1 (Shalhevet, 1994), and Etc of 1 dS·m^{-1} and Sd of 57% per dS·m^{-1} (Shalhevet, 2006). Both sets were based on data obtained in field experiment conducted near Akko, Israel between 1984 and 1992. Shalhevet calculated these coefficients from the relationship between yield and average rootzone salinity, whereas the coefficients we calculated were obtained using the Letey production function. Although different methods were used, the different coefficients result in similar conclusions.

Whatever sets of coefficients are used, 'Hass' avocado on Mexican seedling rootstock is the most salt sensitive crop of the crops with known coefficients (Maas and Grattan, 1999). Also the average ECes projected to result in zero yield according to Eq. [2] are similar: 1.8 to 2.8 dS·m^{-1} for Shalhevet's coefficients as compared to the 2.2 dS·m^{-1} obtained with our coefficients.

The value of Ym, 94 kg·tree^{-1}, is somewhat lower than the maximum potential yields of well managed orchards, 100 to 150 kg·tree^{-1}, postulated by Wolstenholme and Whiley (1992). The value of AWm, 1200 mm/year, is the crop water requirement for conditions where neither soil salinity, nor water, are limiting. The corresponding Kc, 0.86, is obtained by dividing AWm by the ETo of 1390 mm/year. This value of Kc is somewhat higher than the 0.72 reported by Gardiazabal et al. (2003) and considerably greater than the 0.55 – 0.65 reported by Arpaia et al., 1993 and the 0.64 reported by Grismer et al. (2000). Since differences in climatic conditions, size of crop canopies, soil
salinities, irrigation water salinity, and rainfall contribution to crop water can affect Kc values, further discussion about the Kc is beyond the scope of this paper.

Because an ECiw* of 0.68 exceeds the threshold salinity of 0.57 dS·m^{-1}, 2500 mm/year of applied water (Fig. 5) would be required to obtain maximum yields. This would result in an average rootzone salinity that would not exceed the threshold. However the leaching fraction would be 0.52. Leaching fractions greater than about 0.4 are difficult to achieve, and may result in anaerobic conditions, and increased disease pressure. Avocado is unusually sensitive to anaerobic conditions (Stolzy et al., 1967). A leaching fraction of 0.30 is projected to result in maximum yields for an ECiw* of about 0.5 dS·m^{-1} and an AW of 1680 mm. Thus, if maximum potential yields are the goal, ECiw* should be 0.5 dS·m^{-1} or less for 'Hass' avocado grown on Mexican seedling rootstock.

Conclusions

The production function model of Letey et al. (1985) with appropriate coefficients described the observed effects of applied water on yields of 'Hass' avocados on Mexican seedling rootstocks and on leaching fraction. Different amounts of applied water had little or no impact on the average rootzone salinity; neither did they result in Cl levels in the leaves that are associated with leaf injury. Consequently we conclude differences in yields were due to the differences in applied water since the soil-water salinity was also limiting crop water and yields. Yields increased with increasing applied water because trees evapotranspired more water before the ECsw reached a limiting level of about 4 $dS \cdot m^{-1}$.

Because of the unusually high sensitivity of 'Hass' avocado on Mexican seedling rootstocks to salinity and to anaerobic conditions, maximum yields are likely not achievable when irrigated with waters that have an average annual salinity, including correction for rainfall, greater than about 0.5 $dS \cdot m^{-1}$.

References

Allen, R.G., L.S. Periera, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrig. and Drainage Paper no. 56. Food and Agr. Organization. Rome.

Arpaia, M.L., J.L. Meyer, D.S. Stottlemyer, G.W. Witney, and G.S. Bender. 1993. Irrigation and fertilization management of avocado. p. 26-34. In: 1993 Calif Avocado Res. Symp., Univ. of Calif., Riverside, CA, March, 1993. 1 Apr. 2006. <http://www.avocadosource.com/arac/sum_1993/symp_1993_pg_26-34.pdf>

Bernstein, L. and L.E. Francois. 1973. Leaching requirement studies: Sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc. 37:931-943.

Bingham, F.T., L.B. Fenn, and J.J. Oertli. 1968. A sand culture study of chloride toxicity to mature avocado trees. Soil. Sci. Soc. Amer. Proc. 32:249–252.

Bingham, F.T. and C.O. Nelson. 1970. The effects of sodium on mature avocado leaves. Calif. Avocado Soc. Yrbk. 54:75-78.

Embleton, Tom W., W.W Jones, and M.J**.** Garber. 1960. Fertilization of the avocado: leaf analysis as a guide to nitrogen. Calif. Agr. 14(1):12.

Gardiazabal, F., C. Magdahl, F. Mena, and C. Wilhelmy. 2003. Determinacion del coeficiente de cultivo (Kc) para paltos cv. Hass en Chile. p. 329-334. In Actas V Congreso Mundial del Aguacate, Granada-Málaga, Spain, 19-24 Oct. 2003. 1 Apr. 2006. <http://www.avocadosource.com/wac5/papers/wacC5_p329.pdf>

Goodall, G.E., T.W. Embleton, and R.G. Platt. 1981. Avocado fertilization. Univ. of Calif. Div. Agr. Sci., Oakland, Calif., Lflt. 2024.

Grismer, M.E., R.L. Snyder and B.A. Faber. 2000. Avocado and citrus orchards along the coast may use less water. Calif. Agr. 54:25-29.

Gustafson, D. 1976. Avocado water relations. p. 47-53. In: J.W. Sauls, R.L. Phillips and L.K. Jackson (eds.): Proc. 1st Intl. Trop. Fruit Short Course: The Avocado. Fruit Crops Dept., Fla. Coop. Ext. Serv., Inst. Food and Agr. Sci., Univ. Florida, Gainesville, Fla. 1976.

Gustafson, C.D., A. W. Marsh, R. L. Branson, S. Davis. 1979. Drip irrigation on avocados. California Avocado Society 1979 Yearbook. 63:95-134.

Kalmar, D., and E. Lahav. 1977. Water requirements of avocado in Israel. I. Tree and soil parameters. Austral. J. Agr. Res. 28:859-868.

Letey, J., A. Dinar, and K.C. Knapp. 1985. Crop-water production function model for saline irrigation waters. Soil Sci. Soc. Amer. J. 49:1005-1009.

Letey, J. and A. Dinar. 1986. Simulated crop-water production function model for several crops when irrigated with saline waters. Hilgardia. 54:1-32.

Maas, E.V. and S.R. Grattan. 1999. Crop yields as affected by salinity. p. 55-108. In: W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, SSSA, Madison Wis.

Maas, E.V. and G.J. Hoffman. 1977. Crop salt tolerance-current assessment. J. Irrig. Drainage Div., Amer. Soc. Civil Eng. 103:115-134.

Meyer, J.L., M.V. Yates, D.E. Stottlemyer, E. Takele, M.L. Arpaia, G. S. Bender, and G.W. Witney. 1992. Irrigation and fertilization management of avocados. p. 281-288. In C. Lovatt (ed.). Proc. 2nd World Avocado Congr., Orange, Calif., 21-26 Apr. 1991. 1 Apr. 2006.

Mickelbart, M.V and M.L. Arpaia. 2002. Rootstock influences changes in ion concentrations, growth and photosynthesis of 'Hass' avocado trees in response to salinity. J. Amer. Soc. Hort. Sci. 127:649-655.

Oster, J.D. 1984. Leaching for salinity control. p 175-189. In: Y. Shalhevet and I. Shainberg (eds.). Soil salinity under irrigation. Ecol. Studies no. 51. Springer-Verlag. Heidelberg.

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery. 1996. Numerical recipes in FORTRAN 90: The art of parallel scientific computing. 2nd ed. Cambridge Univ. Press. New York.

Richards, S.J., L.V. Weeks, and J.C. Johnston. 1958. Effects of irrigation treatments and rates of nitrogen fertilization on young 'Hass' avocado trees. I. Growth response to irrigation. Proc. Amer. Soc. Hort. Sci. 71:292-297.

Richards, S.J., J.E. Warneke, and F.T. Bingham. 1962. Avocado tree growth response to irrigation. Calif. Avocado Soc. Yrbk. 46:83-87.

Shalhevet, J. 1994. Using water of marginal quality for crop production: major issues. Agr. Water Mgt. 25:233-270.

Shalhevet, J. 2006. Avocado sensitivity to salinity revisited – Akko Experiment 1984-1992. In: R. Hofshi and M. L. Arpaia (eds.). Proc. of brainstorming salinity management. Ventura, CA. 30 Oct, – 1 Nov. 2003. (Hofshi Foundation, In Press)

Solomon, K.H. 1985. Water-salinity-production functions. Trans. Amer. Soc. Agr. Eng. 28:1975-1980.

Stolzy, L.H., George A. Zentmyer, l.J. Klotz, and C.K. Labanauskas. 1967. Oxygen diffusion, water and *Phytophthora cinnamomi* in root decay and nutrition of avocados. J. Amer. Soc. Hort. Sci. 90:67-76.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S.Dept. Agr. Hdbk. No. 60. U.S. Govt. Printing Office, Washington, D.C.

Wolstenholme, B. Nigel, and A. W. Whiley. 1992. Requirements for improved fruiting efficiency in the avocado tree. p. 161-167. In C. Lovatt (ed.) Proc. 2nd World Avocado Congr., Orange, Calif., 21-26 Apr. 1991. 1 Apr. 2006. <http://www.avocadosource.com/wac2/wac2_p161.htm>