# Salinity and Water Effects on 'Hass' Avocado Yields

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ABSTRACT. **A field experiment was conducted between 1992 and 1997 in a commercial orchard of mature 'Hass' avocados on Mexican seedling rootstock (*Persea americana* Mill.) to determine how yield was influenced by the amount of irrigation water applied and the frequency of application. Three amounts of water (targeted at 90%, 110%, and 130% of estimated crop evapotranspiration) were applied at three frequencies (one, twice, and seven times per week) with microsprinklers located beneath the tree canopy. The site was set up as a randomized complete block design with six blocks, each including one replicate of all irrigation treatments. One or two trees located at the center of the replicates were used to measure yields and tree size, and as the locations where samples of soil and soil water were obtained for analysis from beneath the tree canopy. The average electrical conductivity and chloride concentration of the irrigation water, corrected for rain, were 0.7 dS·m$^{-1}$ and 1.8 mmol·L$^{-1}$, respectively. From May 1994 to Nov. 1996, salinity of the saturated-paste extracts of soil samples obtained in the 0- to 120-cm depth interval averaged ≈2 dS·m$^{-1}$ for all irrigation treatments. Irrigation treatments also had little influence on the maximum soil-water salinity, ≈4 dS·m$^{-1}$, in and below the lower portion of the root zone. Consequently, irrigation treatments had little influence on the fraction of applied water that was not used by the crop, the leaching fraction. Chloride concentrations in leaves were affected by applied water but did not attain levels that are associated with leaf injury. Trees irrigated seven times per week had lower yields than trees that received less frequent irrigation. During the last 2 years of the experiment, when yields no longer increased with time, the yields for treatments irrigated once and twice per week increased with increasing amounts of applied water. We were able to explain the influence of both amount of applied water and soil salinity on avocado yields and leaching fraction using production function concepts. Yields increased with increasing amounts of applied water because of increased water availability for crop use before a soil-water salinity of ≈4 dS·m$^{-1}$ restricted water uptake. The threshold salinity above which yield decline occurred was determined to be 0.57 dS·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 ≈0.6 dS·m$^{-1}$.**

Drip irrigation for avocados was first experimentally introduced into California from Israel in the late 1960s (Gustafson, 1976). Gustafson et al. (1979) compared drip irrigation of 'Hass' avocado on Mexican seedling rootstock with the then standard sprinkler irrigation method in a plot located in San Diego county, Calif. The electrical conductivity of the irrigation water (ECiw) was ≈1.0 dS·m$^{-1}$. This study was prompted by the rising cost and limited supplies of irrigation water in southern California. For both the irrigation treatments, sufficient water was applied to maintain the soil water matric potential greater than –20 kPa at the 30-cm and 60-cm depths beneath the tree canopy. The salinities of saturated paste extracts (ECe) of soil samples obtained in the 0- to 90-cm depth interval were determined 10 times between Fall 1970 and Spring 1976. The average ECe for sprinkler was 2.2 dS·m$^{-1}$ and for drip it was 2.0 dS·m$^{-1}$.

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 results reported previously by Kalmar and Lahav (1977) and Richards et al. (1958). The Meyer project was followed up by the study described in this article, which initially aimed to examine the relationship between irrigation amount and frequency on yield and tree growth of 'Hass' avocado on Mexican seedling rootstock.

We found that yield increased with increasing amounts of applied water (average ECiw of ≈0.7 dS·m$^{-1}$) and that the amount of applied water had little influence on the average ECe in the root zone, 2 to 3 dS·m$^{-1}$. This result is similar to that reported previously by Bingham and Richards (1958) and Kalmar and Lahav (1977) for the same avocado/rootstock combination in which ECiw ranged from 0.5 to 0.8 dS·m$^{-1}$ and Cl concentration in the irrigation water ranged from 1.1 to 1.3 mmol·L$^{-1}$. Kalmar and Lahav (1977) reported maximum ECe levels in the root zone ranging from 1.8 to 2.0 dS·m$^{-1}$ obtained in a field experiment conducted near Akko, Israel. In the study conducted by Richards et al. (1958) at the University of California, Riverside, ECe increased little with decreasing applied water, although one of the treatments was purposefully underirrigated. The largest increase was from 1.6 dS·m$^{-1}$ for the treatment irrigated with the most water to 2.2 dS·m$^{-1}$ for the treatment receiving the least water (Bingham and Richards, 1958). The ECe data reported by Bingham and Richards (1958), Gustafson et al. (1979), and Kalmar and Lahav (1977) are surprisingly similar, averaging ≈2 dS·m$^{-1}$, considering the different experimental conditions under which they were obtained.

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An ECe of ≈2 dS·m$^{-1}$ could be a salinity level that limits water uptake (Bernstein and Francois, 1973) by Mexican seedling rootstocks. If this is the case, 'Hass' avocado on Mexican seedling rootstock is extremely salt-sensitive. The observations of Bingham and Richards (1958), Gustafson et al. (1979), and Kalmar and Lahav (1977) suggest that both the amount of applied water and soil salinity in the root zone, at unusually low levels, are both factors that could limit avocado yields.

The combined influence of applied water and root zone salinity on crop yields is the focus of crop-water production functions developed in the 1980s (Letey and Dinar, 1986; Letey et al., 1985; Solomon, 1985) and are currently used (Shani and Ben-Gal, 2005; Shani and Dudley, 2001) for different crops. 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 ECiw equals zero, yields are assumed to increase linearly between a threshold amount of applied water (AWt) and an amount (AWm) that results in maximum yield (Ym) based on reports by de Wit (1958) and Hanks (1974). 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. The relationship between average root zone salinity and leaching fraction is based on an exponential uptake function proposed by Raats (1974). Maas and Hoffman (1977) reported that crop yields generally are unaffected by root zone salinity until they reach a threshold value (ECt) and then decline linearly with increasing average root zone salinity [Sd (percentage decline per dS·m$^{-1}$)]. These coefficients are an integral part of the production function model of Letey et al. (1985). Because this model accounts for the influence of both the amount of applied water and root zone salinity on crop water use and crop yield, it was used to evaluate the results we obtained.

## Materials and Methods

**Location.** The 10-ha experimental site with 10- to 15-year-old 'Hass' avocado on Mexican seedling rootstock was located at lat. 33°17′10″N and long. 117°8′5″W, ≈20 km north of Escondido, Calif. The site had a southern exposure with an average slope of 16% (standard deviation = 6%). The soil was Cieneba coarse sandy loam (pH 6) classified as a thermic, shallow Typic Xerorthents (Soil Conservation Service, 1973).

Climate at the site from May 1993 through Apr. 1997 had the following average characteristics based on weather data collected from the nearest CIMIS station, ≈30 km northwest of the site (Temecula Station, number 62): potential evapotranspiration = 1390 mm/year, rainfall = 464 mm/year, wind speed = 1.7 m·s$^{-1}$, minimum relative humidity = 42%, and average relative humidity = 63%. August was the hottest month with an average daytime temperature of 24 °C. December was the coldest month with an average daytime temperature of 13 °C. A Class A evaporation pan and rain gauge were located in an open area along the south side of the project area.

**Experimental layout and irrigation system.** The original tree spacing was 6.1 × 6.1 m (≈269 trees/ha). In Spring 1992, every other tree was removed along the diagonal, increasing the spacing to 8.6 × 8.6 m (135 trees/ha).

After consultation with a biometrician, the experimental site was set up as a randomized complete block design with six blocks, each including one replicate of all irrigation treatments. One or two trees located at the center of replicates, designated as record trees, were used to measure yields and tree size. Soil and soil-water samples were taken beneath the canopy of the record trees. Blocks two through six had two record trees per replicate where one record tree was set aside for soil sampling and the other was used for installation of tensiometers and extraction cups. Block one had one record tree, which was the site for all soil measurements.

All record trees were topped to ≈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.

The nine irrigation treatments consisted of three amounts of applied water per week with each amount applied at three frequencies. 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 onsite and assumed crop coefficient. The three frequencies of irrigation were once (F1), twice (F2), and seven (F7) times per week.

The existing under-canopy sprinkler irrigation system was replaced with a new system during Aug. and Sept. 1992. A single microsprinkler for each tree was located ≈1 m from the tree trunk in close proximity to the original sprinkler. This minimized changes in the soil-wetting pattern associated with switching irrigation systems. A single mainline served each combination of applied water and irrigation frequency in all blocks. Foot valves in the nine mainlines prevented drainage through the sprinklers located at lower elevations at the end of the irrigation cycle. A 12-station controller, water meters, and valves were used to control and measure the amount of irrigation water applied to each plot and the remaining trees at the site that were not part of the experiment.

From 1992 through approximately Dec. 1995, the microsprinklers were 3 cm tall and delivered 91 L·h$^{-1}$. During Winter 1995–1996, these sprinklers were replaced with 3-cm-tall, 130-L·h$^{-1}$ microsprinklers that were mounted on 15-cm-tall risers. This reduced labor to remove leaf litter to maintain a clear field of throw. The throw radius of both sprinklers was ≈210 cm. After each set of sprinklers was installed, the distribution of applied water was measured at each record tree at 60-cm intervals along four 240-cm-long 90° radials centered on the sprinkler. The amount applied at 90 cm equaled the average application depth for both sets of sprinklers. The time to discharge 1 L was determined annually for all sprinklers located beneath the record trees; the coefficient of variation ranged from 0.05 to 0.07.

**Water management and water quality.** Irrigation scheduling occurred once per week, usually on Mondays. The cumulative evaporation (ETpan) of the previous week from the onsite Class A pan was used to determine irrigation for the next week. The intention was to recharge the water removed from the soil during the previous week. The amount of water (AW) required for the area covered by the tree canopy was calculated using the following equation:

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

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. AW was converted to the corresponding operating time to program the irrigation controller based on the following considerations: 1) average discharge rate of the microsprinklers; 2) irrigation frequency; 3) rainfall correction, if appropriate; 4) appropriate conversion factors; and 5) canopy area. Eq. [1] did not include a pan coefficient (Allen et al., 1998) because ETpan was the same as the ETo measured at the CIMIS Temecula Station. No correction for runoff was made in Eq. [1] because none was observed at any time during the experiment.

Corrections for rainfall were made by subtracting the total rainfall of the previous week from the amount of water to be applied during the upcoming week. Where rainfall from the previous week exceeded the calculated AW for the next week, no irrigation occurred. The rain correction was carried forward for only 30 d; in other words, the remaining excess of rainfall at the end of 1 month was not subtracted from calculated AW for the next month.

The Valley Center Municipal Water District supplied the irrigation water, a blend of well water and Colorado River water. Eighteen water samples obtained between Mar. 1992 and Dec. 1996 had the following quality characteristics: ECiw ranged from 0.7 to 1.1 $dS \cdot m^{-1}$ and averaged 1.0 $dS \cdot m^{-1}$; Cl concentration ranged from 2.3 to 3.1 $mmol \cdot L^{-1}$ and averaged 2.7 $mmol \cdot L^{-1}$; 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.

**Monitoring of soil-water salinity and matric potential.** Soil-water samples obtained by imposing a vacuum of ≈–70 kPa on ceramic extractors were analyzed for electrical conductivity (ECsw). These ceramic extractors were installed 0.9 m from both the sprinkler and tree trunk at the 30-cm 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. Samples were collected every 2 to 3 weeks from approximately December through June, whenever soil-water matric potentials were greater than ≈–40 kPa. Only a few samples were obtained from July through November because of low water potentials; a total of 779, 797, and 221 samples were obtained for the 30-cm, 60-cm, and 120-cm depths, respectively.

Soil samples were taken in November and May each year and the saturation paste extracts (U.S. Salinity Laboratory Staff, 1954) were analyzed for pH, ECe, Na, and Cl. These soil samples were collected beneath the record trees along a circumference of 0.9 m from the sprinkler at depth intervals of 0–15, 15–30, 30–60, and 60–120 cm. This distance from the sprinkler was where the spatial distribution of the application rates equaled the average application rate. The sampling hole was filled, and the next sampling site was marked at a location ≈50 cm from the filled sampling hole. The gravimetric water content was measured on the soil samples obtained in Nov. 1992, 2 months after the start of irrigating with the experimental system.

In July 1994, transducer-equipped tensiometers were installed 0.9 m from the microsprinkler and the tree trunk beneath the record tree not used for soil sampling. 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. Tensiometers were serviced once per week, except during the summer, when they were occasionally serviced twice per week. If suction was broken, they were refilled and pumped to remove any air.

**Monitoring of tree growth, chemical composition of leaves and roots, root distribution, and crop yields.** Tree growth was monitored annually by measuring trunk circumference 20 cm above the bud union, canopy area, and tree height. The initial trunk circumference in 1992 was used to calculate the relative increase in trunk circumference for each succeeding year. Tree height was first measured in Feb. 1993 and the tree area in Nov. 1993. The width of the tree, represented by the outer limits of most of the tree limbs, was measured in the north–south and east–west directions and averaged to obtain a diameter to calculate the ground area covered by the tree. After 1993, tree growth measurements were made annually in November and December.

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 (Embleton et al., 1960). Recently expanded, fully mature leaves from nonflushing, nonfruiting branches that were less than 2 m above the ground were collected washed and dried. The leaves were analyzed for N, P, K, S, Ca, Mg, Na, Cl, B, Zn, Mn, Fe, and Cu.

Roots were extracted from soil samples obtained in Aug. and Sept. 1995 at 0.9 m from both the tree trunk and sprinkler in all replicates of the irrigation treatments in blocks 2 through 6. Samples were obtained at the 0- to 8-cm, 8- to 15-cm, 15- to 30-cm, and 30- to 60-cm depth intervals with a 5-cm-diameter bucket auger. Roots were separated from the soil by washing the sample in a bucket using a forceful stream of water and hand agitation. The roots and leaf litter were decanted onto a 2-mm sieve and the leaf litter removed. The roots were then placed onto a fine meshed screen, rinsed with deionized water, and transferred to a plastic sheet with markings indicating the dimensions of the scanner used to measure the number and length of the roots. Special care was taken so that roots did not overlap or form a loop on the plastic sheet. After scanning, the wet and dry (≈60 °C) weights of the roots were measured and analyzed for Ca, Mg, Na, and Cl.

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.

**Production Function Analysis.** 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, 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 were done using the General Linear Model (Minitab, release 13.1; Minitab, State College, Pa.). The Tukey method was used for pairwise comparisons among means with probabilities less than 0.055 considered significant unless otherwise noted.

Crop yields for the first crop season, May 1992 to Apr. 1993, were not included because the yields reflected conditions before the initiation of the study. Although there were no statistical differences in yields among the water treatments for the 1993–1994 crop season, yields and growth parameters for this season were included in the statistical analysis to include the total time differential treatments could have been influential. Also, a statistical analysis of yields for the 1995–1996 and 1996–1997 crop seasons was done, which excluded data for the F7 treatments.

Using relative increase in trunk diameter, or tree area, as a covariant in the statistical analysis of crop yields resulted in only a 4% reduction in adjusted mean square. Consequently, a covariant was not used in the statistical analysis of crop yields. The log-transformed yields were more normally distributed than the untransformed yields. However, the conclusions about treatment effects were the same using both transformed and untransformed data. Consequently, untransformed yields were used for the statistical results reported here.

The ECe data were grouped by sampling date, May and November, for statistical analysis, whereas the ECsw data were grouped by crop season.

## Results and Discussion

**IRRIGATION MANAGEMENT.** The water application targets of 0.9, 1.1, and 1.3 times estimated crop evapotranspiration (ETc) were exceeded as a result of an inability to fully correct for rainfall (Tables 1 and 2). The average excess resulting from 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·d$^{-1}$). Reduction in applied irrigation water to fully account for rainfall would have required carrying the rain correction forward from 1 month to the next for 3 to 6 months.

The fraction of applied water that was rain ranged from 0.28 for the AW3 treatment to 0.36 for the AW1 treatment (Table 2). Assuming the average annual rainfall (390 mm) was available, either for water use by the crop or for leaching, rainfall had a significant effect on ECiw. The weighted-average EC of the combined irrigation and rainfall, ECiw*, ranged from 0.69 to 0.72 compared with an ECiw of 1 dS·m$^{-1}$ (Table 2). Similarly, the rain reduced the weighted-average Cl concentration, Cliw*, from 2.7 to 1.83 mmol·L$^{-1}$.

The depths of applied water (Tables 1 and 2) do not provide a perspective on the soil depth wetted during individual irrigations, particularly during the summer. The maximum weekly ETpan, ≈55 mm, occurred during July and August. The corresponding weekly irrigation for AW3F1, the treatment that received the most water during an individual irrigation, is 49 mm based on Eq. [1]. From Mar. 1995 through May 1997, the tree canopy area used to calculate the amount of water to apply was 47 m$^2$, whereas the area wet by the sprinkler was 14 m$^2$. Consequently, instead of applying 49 mm of water to 47 m$^2$, 160 mm was applied to 14 m$^2$. The estimated depth of water in the 0- to 120-cm depth interval (Table 3), based on the soil-water contents determined in Nov. 1992, ranges from 167 to 225 mm for bulk densities of 1.4 and 1.9 g·cm$^{-3}$, respectively, the range in bulk densities of soils with sand textures (Skopp, 2000). The addition of 160 mm of irrigation water could increase the depth of water in the 0- to 120-cm depth interval to 327 to 385 mm, amounts sufficient to saturate the soil to depths of ≈70 cm for a bulk density of 1.4 g·cm$^{-3}$ and 140 cm for a bulk density of 1.9 g·cm$^{-3}$. These depths were estimated assuming a soil particle density of 2.65 g·cm$^{-3}$, which results in volumetric water contents of saturated soils of 0.47 and 0.28 mm$^3$·mm$^{-3}$ with bulk densities of 1.4 and 1.9 g·cm$^{-3}$, respectively. Thus, if the bulk density was 1.9 g·cm$^{-3}$, and there was no lateral wetting beyond the throw radius of the sprinkler, a weekly 17-h irrigation for AW3F1 could have resulted in a temporarily saturated soil in the 0- to 120-cm depth interval. Had saturated soil conditions been a common occurrence in July and August for the AW3F1 treatments, it would have been possible to obtain soil-water samples using the ceramic extractors. This did not occur, indicating that matric potentials greater than –40 kPa did not occur because lateral water movement occurred beyond the throw radius of the sprinkler or did not exist long enough to obtain a water sample. We conclude that the depths of applied water during summer adequately matched water retained in the 0- to 120-cm depth interval for AW3F1 and for the other treatments as well, because they involved application of less water.

**INFLUENCES OF IRRIGATION MANAGEMENT ON SOIL-WATER MATRIC POTENTIAL, ECE, ECSW, AND LEACHING FRACTION.** In 1996 (Fig. 1), soil-water matric potentials at the 30-cm depth

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 yr May–April | ETpan | ETc | Rain | AW1[z] | AW2 | AW3 |
|---|---|---|---|---|---|---|
| | (mm/yr) | | | | | |
| 1993–1994 | 1390 | 790 | 340 | 690 | 830 | 1000 |
| 1994–1995 | 1370 | 790 | 680 | 600 | 740 | 870 |
| 1995–1996 | 1320 | 760 | 190 | 710 | 840 | 1010 |
| 1996–1997 | 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 onsite.

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 EC (ECiw*) and Cl concentration (Cliw*) of the irrigation water and rain.

| Irrigation treatment | AW1[z] | AW2 | AW3 |
|---|---|---|---|
| Average applied, including rainfall (mm/yr) | 1080 | 1220 | 1380 |
| Average target (mm/yr) | 720 | 880 | 1040 |
| Excess irrigation (mm/yr) | 360 | 340 | 340 |
| Fraction rainfall | 0.36 | 0.32 | 0.28 |
| ECiw* corrected for rain (dS·m$^{-1}$)[y] | 0.64 | 0.68 | 0.72 |
| Cliw* corrected for rain (mmol·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 onsite.

[y]The electrical conductivity of the irrigation water (ECiw) averaged 1.0 dS·m$^{-1}$ and the chloride concentration (Cliw) of the irrigation water averaged 2.7 mmol·L$^{-1}$. The corresponding values for rain are 0.0.

Table 3. The gravimetric field water content in Nov. 1992 and corresponding depth of water in the depth interval based on the range in bulk densities ($\rho_b$) for sand textures.

| Soil depth interval (cm) | Gravimetric field water content (%)[y] | Depth of water [z] (mm) $\rho_b$ = 1.4 g·cm$^{-3}$ | $\rho_b$ = 1.9 g·cm$^{-3}$ |
|---|---|---|---|
| 0–15 | 18.0 d | 38 | 51 |
| 15–30 | 11.3 c | 24 | 32 |
| 30–60 | 9.5 b | 40 | 54 |
| 60–120 | 7.7 a | 65 | 88 |

[y]Based on the Tukey pairwise comparison among means, those within rows followed by different letters were significantly different ($P$ < 0.055).
[z]Depth of water (mm) equals length of depth interval × 10 × 0.01 × gravimetric water content × $\rho_b$.

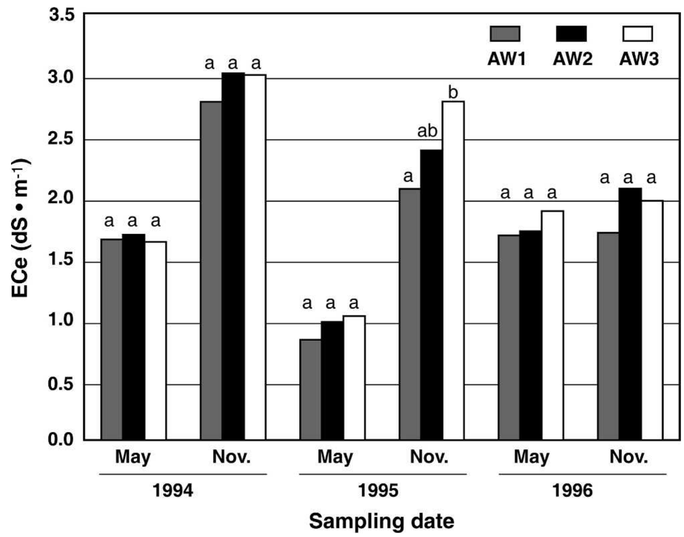


Fig. 2. Influence of applied water treatment (AW) on the average electrical conductivity of saturation paste extracts (ECe) at a soil depth of 0 to 120 cm. Soil samples were collected in May and November of each year (1994–1996). The irrigation amounts were 0.9 (AW1), 1.1 (AW2), and 1.3 (AW3) times the estimated crop water requirement based on the pan evaporation measured onsite.

for AW2 decreased more quickly for F7 and remained at more negative levels than for F2 and F1. In both 1995 (data not shown) and 1996, this difference became evident approximately 15 Apr. and lasted until approximately 1 Nov., a time period that includes the warmest and driest months of the year. The resulting lower soil-water matric potentials in F7, and consequently also lower soil-water contents, likely resulted from relatively greater amounts of water lost at the soil surface by direct evaporation to air than for F2 and F1. This likely occurred for F7 because the soil surface was wetted each day and depth of applied water was smaller than for F2 and F1.

The average ECe for the 0- to 120-cm depth interval, from May 1994 to Nov. 1996, was affected little by irrigation treatment (Fig. 2) except in Nov. 1995. Also, there was no general increase in ECe during this period. This confirms that the crop did not use all of the applied water and that leaching occurred throughout the experiment. Consequently, salt accumulation in the 0- to 120-cm depth interval did not occur because salts applied in the irrigation water were moved downward through the root zone to greater depths.

The 1994–1995 crop year had the most rainfall (Table 1) causing the large reduction in ECe between Nov. 1994 and May 1995 (Fig. 2). November 1995 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. This supports the findings of others that 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).

The interaction, AW × F, was significant ($P$ = 0.008) because of differences among the average ECes in November (Fig. 3). For F1, there were no significant differences among the average ECes for the AW treatments, whereas there were for F2 and F7.

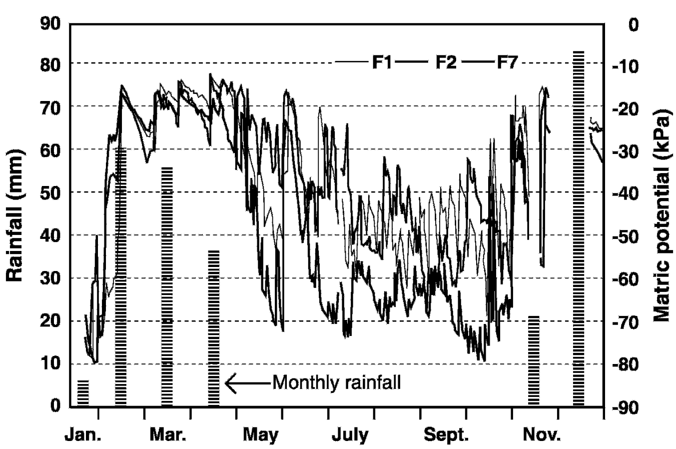


Fig. 1. Effects of irrigation frequency on soil-water matric potential. Data presented is from 1996. Readings collected from the 30-cm depth from the applied water (AW) 2 treatment (1.1 times the estimated crop water requirement). Irrigation frequency treatments were once per week (F1), twice per week (F2), and seven times per week (F7).

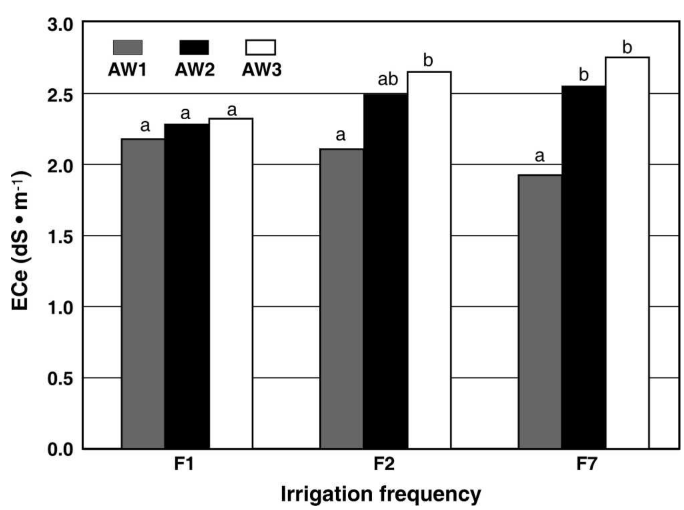


Fig. 3. Applied water (AW) by irrigation frequency (F) interaction for the average electrical conductivity of saturation paste extracts (ECe) at a soil depth of 0 to 120 cm for soil samples collected in November of each year (1993–1996). Columns with the same letters on the top indicate the means are not significantly different within an irrigation frequency. The 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 onsite. Irrigation frequency treatments were once per week (F1), twice per week (F2), and seven times per week (F7).

As irrigation frequency increased, the greater the AW, the greater the ECe. This can be associated with increasing water loss by evaporation to air as irrigation frequency increases and with increasing amount of applied salt as AW increases. Consequently, in November, there were no significant differences among the three AW treatments for F1, whereas there were significantly higher ECes for AW3 within both F2 and F3 (Fig. 3).

Like ECe, water treatment had a small influence on ECsw. There were significant effects of crop year [CY ($P$ = 0.000)], depth [D ($P$ = 0.001)], and AW ($P$ = 0.001) and interactions among these factors and with irrigation frequency for the 1994–1995, 1995–1996, and 1996–1997 crop seasons. Because of the large amount of rainfall in the 1994–1995 crop year, ECsw in the 0- to 120-cm interval increased during the succeeding crop years: 3.0 $dS \cdot m^{-1}$ in 1994–1995, 4.0 in 1995–1996, and 4.7 in 1996–1997 with all differences being significant. The average ECsw for the 30-cm, 60-cm, and 120-cm depths was 3.3, 3.8, and 3.6 $dS \cdot m^{-1}$, respectively, with only the averages for the 30-cm and 60-cm depths being significantly different. The average ECsw for AW1, AW2, and AW3 was 3.5, 3.2, and 4.0 $dS \cdot m^{-1}$, respectively, with only the averages for AW2 and AW3 being significantly different. Although the CY × D interaction was significant ($P$ = 0.000), there was no clear trend in the averages for ECsw. The minimum value, 2.3 $dS \cdot m^{-1}$, was obtained at 30 cm in 1994–1995 and was significantly lower than the maximum value, 5.2 $dS \cdot m^{-1}$, obtained at 60 cm in 1996–1997. For the significant interaction, AW × F × D ($P$ = 0.000), there were no significant differences among the means for the 120-cm depth. The maximum values at the 60-cm depth, 4.2 and 5.3 $dS \cdot m^{-1}$, occurred in the AW3F7 and AW3F2 treatments, respectively. These were significantly higher than the minimum values at the 30-cm and 60-cm depths, 2.8 and 3.1 $dS \cdot m^{-1}$, respectively, that occurred for AW3F1, AW1F1, and AW1F2. The effects of AW and F at the 30-cm and 60-cm depths were consistent with their effects on ECe. The treatment that applied the most water and salt, AW3, in combination with F1 and F2, resulted in the greatest ECsw, and the lowest values occurred for F1 and F2, which we associate with the less water lost by direct evaporation to air than occurred in F7.

The ECsw measurements, made from November and June when the soil-water potential was higher than –40 kPa, reflect the wettest conditions during the experiment. Consequently, ECsw was determined when leaching was occurring at the greatest rate during the crop year. Based on the root distribution with depth (Fig. 4), we consider both the 60-cm and 120-cm depths to be near to, or below, the bottom of the root zone. Consequently, we assume the average ECsw of the 60-cm and 120-cm depths for all treatments, 3.7 $dS \cdot m^{-1}$, as a good estimate of the average EC of the drainage water, ECdw, for all irrigation treatments. ECdw is used to calculate the leaching fraction.

Leaching fraction is defined as the ratio of the volume of drainage water divided by the volume of applied water (U.S. Salinity Laboratory Staff, 1954). Assuming no calcite dissolution or precipitation, leaching fraction equals ECiw* divided by ECdw (Oster, 1984). 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-cm and 120-cm depths, respectively, the maximum range of leaching fractions would be from 0.13 to 0.27.

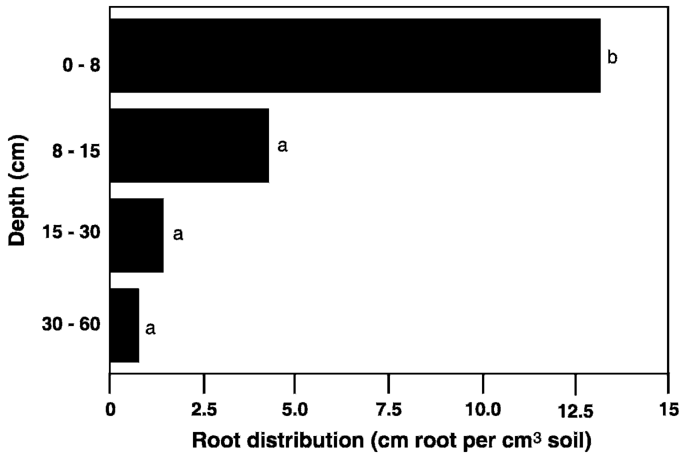


Fig. 4. Average root distribution by soil depth (cm root per $cm^3$ soil). Roots sampled in Aug. to Sept. 1995.

In regard to correction for calcite dissolution or precipitation, the soil at the experimental site is acidic (Soil Conservation Service, 1973). Consequently, the soil would not contain calcite negating the possibility of calcite dissolution. The concentration of calcium (1.0 $mmol \cdot L^{-1}$) and bicarbonate (1.8 $mmol \cdot L^{-1}$) in the irrigation water contribute ≈29% of the total dissolved salts in the rain-corrected composition of the irrigation water. Based on estimates calculated using WATSUIT (Oster and Rhoades, 1990), correction for calcite precipitation is insignificant unless the leaching fraction is less than ≈0.10, which is lower than leaching fractions we obtained.

The main findings of this section are that the effects of the AW treatments on ECe, ECsw, and leaching fraction were small. The ECe within the root zone was variable but averaged ≈2 $dS \cdot m^{-1}$ (Fig. 2), similar to the values reported by Bingham and Richards (1958), Gustafson et al. (1979), and Kalmar and Lahav (1977). Apparently, the ability of the trees to extract soil-water beyond a limiting ECsw of 4 to 5 $dS \cdot m^{-1}$ was restricted and both the amount of applied water and soil salinity influenced evapotranspiration. 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 restricted water uptake.

**Influences of irrigation management on growth, leaf composition, root distribution, and yield of avocados.** The record trees grew considerably after being topped in 1992. Tree height 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 heights for the AW1, AW2, and AW3 treatments were 7.6, 7.6, and 8.0 m, respectively, with height for the AW3 being 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 $m^2$ for AW2 and 40 $m^2$ for AW1. The effects of irrigation frequency were not significant for either growth parameter nor were interactions between AW, F, and year significant.

Year-to-year increases in relative trunk circumference as compared with 1992 were all significant. Effects of applied water were not significant, whereas irrigation frequencies were ($P < 0.049$). However, the differences among the frequency treatments were small, and the probabilities of the differences among the means were all greater than 0.055. The interactions among AW, F, and year were not significant.

Annual leaf analysis indicated 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 were evaluated because these are the years that are the focus of water treatment effects 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). Injurious levels of Na were not expected because the sodium adsorption ratio (U.S. Salinity Laboratory Staff, 1954) of the applied water ranged from 2.0 to 3.7 $(mmol \cdot L^{-1})^{0.5}$ and averaged 2.6 $(mmol \cdot L^{-1})^{0.5}$, which is lower than the sodium adsorption ratio of 4 considered to be a hazardous level (Bingham and Nelson, 1970). 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. 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. Cl concentration for F1, 107 $mmol \cdot kg^{-1}$, was significantly lower than for F2, 121 $mmol \cdot kg^{-1}$, and for F7, 124 $mmol \cdot kg^{-1}$. Mickelbart and Arpaia (2002) observed no leaf damage where the average Cl concentration in the leaves of 'Hass' on three different clonal rootstocks was $\approx$130 $mmol \cdot kg^{-1}$ and slight leaf damage at 180 $mmol \cdot kg^{-1}$. Bingham et al. (1968) reported slight leaf injury for 6-year-old 'Hass' leaves on the same rootstocks at a Cl concentration of 135 $mmol \cdot kg^{-1}$. Consequently, although water treatment did influence Cl concentration of leaves in Sept. 1995 and 1996, the highest Cl concentrations, 124 $mmol \cdot kg^{-1}$, were less than would be expected to cause leaf injury.

There were no significant effects of the AW or F treatments on root length (Fig. 4), or dry weight, in the 0- to 60-cm depth interval. Root length (Fig. 4) decreased rapidly with depth: from 13.6 $cm \cdot cm^{-3}$ in the upper 8 cm of soil to 0.8 $cm \cdot cm^{-3}$ between 30 to 60 cm (Fig. 4). This root distribution with depth is shallower than that reported by Michelakis et al. (1993) or Salazar-Garcia and Cortés-Flores (1986) for avocado but is in line with distribution patterns reported by Meyer et al. (1992). Effects of AW on the Ca, Mg, Na, and Cl concentration in root tissue were not significant. Effects of irrigation frequency were significant for Mg ($P = 0.002$) and Na ($P = 0.009$). The Mg concentration of 41 $mmol \cdot kg^{-1}$ for F1 was significantly lower than the 57 $mmol \cdot kg^{-1}$ for F7; likewise, the Na concentration of 110 $mmol \cdot kg^{-1}$ for F1 was significantly lower than the 170 $mmol \cdot kg^{-1}$ for F7. The greater concentrations of Mg and Na for F7 likely reflect longer durations of high soil salinities in the upper portion of the root zone consequent to the greater direct loss of water by evaporation in this treatment.

There was a general increase in yield during the four crop years for the F1 and F2 treatments. For all water treatments, the average yields of 41 kg/tree for 1995–1996 and 46 kg/tree for 1996–1997 were significantly greater than the 12 kg/tree for 1993–1994 and 25 kg/tree for 1994–1995. 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 1995–1996, the yield for F1, 59 kg/tree, was significantly greater than in 1993–1994, 11 kg/tree; for F2, the yield in 1995–1996, 61 kg/tree, was significantly greater than the 14 kg/tree in 1993–1994. For F7, there was no year when the yield was significantly greater than the 12 kg/tree in 1993–1994. We believe this was the result of the limiting levels of ECsw in the root zone occurring sooner for F7 than for F2 and F1 resulting from the greater relative water lost by direct evaporation to air for F7 than for F2 and F1. Daily sprinkler irrigation would not be a recommended practice, especially with saline water. Consequently, 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). This function was derived for conditions in which water management under field conditions is consistent with recommended practices.

Yield efficiency, the yield per unit of tree canopy, during the 1995–1996 and 1996–1997 crop seasons, averaged 0.15 $kg \cdot m^{-3}$ and was not consistently affected by the AW or by F. In the 1995–1996 crop season, yield efficiency increased significantly with increasing applied water and decreased significantly with increasing irrigation frequency. However, similar trends were not obtained in the 1996–1997 crop season.

The main findings of this section are that tree growth increased with increasing applied water as did crop yields. However, for F7, yield did not increase through four succeeding crop seasons. We believe this was the result of soil-water salinities reaching limiting levels in the upper 15 cm of soil, where most roots were located, earlier in the crop year in F7 than in the F2 and F1 treatments. 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 yields increased with increasing applied water for the 1995–1996 and 1996–1997 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. The yields for AW1 and AW3 are significantly different at the $P < 0.001$ level, and those for AW2 and AW3 are significantly different at the $P < 0.08$ level of significance. Crop yields and associated total applied water for the two crop seasons are shown in Figure 5A along with standard errors of the means. 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. 5B). 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 $dS \cdot m^{-1}$ (ECt) and 63% per $dS \cdot m^{-1}$ (Sd) as the Maas-Hoffman coefficients in the Mass-Hoffman equation (Maas and Hoffman, 1977),

$$Y = 100 - Sd(ECe - ECt) \qquad [2]$$

where Y is relative yield, results in a Y of 0 for an ECe of 2.2 $dS \cdot m^{-1}$. This corresponds to an ECsw 4.4 $dS \cdot m^{-1}$ ($\approx 2 \times$ ECe;

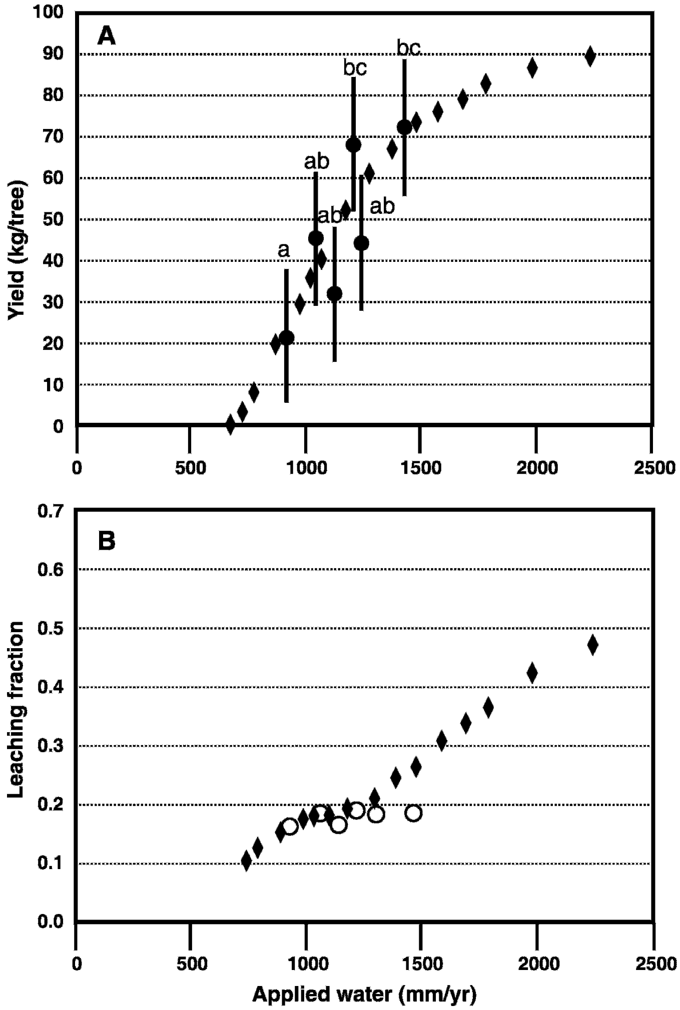


Fig. 5. (**A**) Projected and measured yield of 'Hass' avocado on Mexican seedling rootstock as influenced by the amount of applied water. Bar heights equal two times the standard error and are centered on the average yields obtained for irrigation treatments irrigated once (F1) and twice per week (F2) (add years). (**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. Projections are based on production function coefficients obtained using the measured yields and leaching fractions shown in the figure. Leaching fraction is the ratio of the electrical conductivity (EC) of the irrigation water corrected for rain divided by the EC of the drainage water.

Letey et al., 1985). At depths of 60-cm and 120-cm, only the ECsw of 5.3 dS·m$^{-1}$ obtained for AW3F2 exceeded 4.4 dS·m$^{-1}$. Consequently, the values of Etc and Sd that were obtained using the production function are consistent with expectations based on Eq. [2], that water uptake by 'Hass' avocados on Mexican seedling rootstocks is restricted where the ECsw in the root zone is ≈4.4 dS·m$^{-1}$, which corresponds to an ECe of 2.2 dS·m$^{-1}$. This limiting ECe is consistent with the limiting ECe levels of ≈2 dS·m$^{-1}$ obtained by Bingham and Richards (1958) and by Kalmar and Lahav (1977).

Shalhevet has reported two sets of Maas-Hoffman coefficients for 'Hass' avocado on Mexican seedling rootstocks: ECt of 0.6 dS·m$^{-1}$ and Sd of 80% per dS·m$^{-1}$ (Shalhevet, 1994) and ECt 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 root zone salinity, whereas the coefficients we calculated were obtained using the Letey production function because the AW treatments had little effect on ECe. Although different methods were used, the different coefficients result in a similar conclusion. For Shalhevet's coefficients, the average ECes projected to result in zero yield, 1.8 to 2.8 dS·m$^{-1}$, using Eq. [2] are similar to the 2.2 dS·m$^{-1}$ obtained with our coefficients. 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). The tuber yield of jerusalem artichoke (*Helianthus tuberosus* L.) has an ECt 0.4 dS·m$^{-1}$. However, its Sd is only 9.6% per dS·m$^{-1}$. Strawberry (*Fragaria* L.) has an ECt of 1.0 dS·m$^{-1}$ and its Sd is 33% per dS·m$^{-1}$ (Maas and Grattan, 1999).

The value of Ym, 94 kg/tree, is somewhat lower than the maximum potential yields of well-managed orchards, 100 to 150 kg/tree, postulated by Wolstenholme and Whiley (1992). The value of AWm, 1200 mm/year, is the crop water requirement for conditions in which neither soil salinity nor water is 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 0.64 reported by Grismer et al. (2000). A complete discussion of these Kc values would require careful assessment of whether the reported Kc values could have been affected by differences in climatic conditions, size of crop canopies, soil salinities, irrigation water salinity, rainfall contribution to crop water use, and amounts of applied water. Some of the needed information was not reported by Gardiazabal et al. (2003) and Grismer et al. (2000), and therefore further discussion about the Kc is beyond the scope of this article.

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 root zone salinity that would not exceed the threshold. However, the leaching fraction would be 0.52. Leaching fractions greater than ≈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). Based on our experiences working with farmers in California with various crops and soils, leaching fractions of 0.30 are achievable for sand and loam textured soils. A leaching fraction of 0.30 is projected to result in maximum yields for an ECiw* of ≈0.5 dS·m$^{-1}$ and an AW of 1680 mm. Thus, if maximum potential yields are the goal, ECiw* should be 0.6 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 dependence of yields of 'Hass' avocados on Mexican seedling rootstocks on applied water and its salinity as well as the small impact of the amount of applied water on leaching fraction. The threshold salinity of 0.57 dS·m$^{-1}$ is one of the lowest known for crops (Maas and Grattan, 1999) and the yield loss per unit salinity above the threshold, 63% per dS·m$^{-1}$, is the highest.

Different amounts of applied water had little or no impact on the average root zone salinity; also, they did not result in Cl levels in the leaves that are associated with leaf injury. Consequently, we conclude differences in yields were the result of the differences in applied water because the soil-water salinity was also limiting yields. Yields increased with increasing applied water because trees evapotranspired more water before the ECsw reached a level of ≈4 dS·m$^{-1}$, which restricted water uptake.

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 ≈0.6 dS·m$^{-1}$.

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