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Application efficiency of micro-sprinkler irrigation of almond trees

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Abstract

Micro-sprinklers are becoming a preferred irrigation method for water application in orchards. However, there is relatively little data available to support a particular irrigation scheduling method. The objective of this study is to quantify the components of the water balance of an almond tree under micro-sprinkler irrigation. For that purpose, an experimental plot around an almond tree with an area of 2.0 m × 2.0 m without vegetation, representing about one quarter of the wetted area of the micro-sprinkler was instrumented with neutron access tubes, tensiometers and catch cans. Twenty-five access tubes with catch cans were distributed in a square grid of 0.5 m × 0.5 m, to a depth of 0.9 m. Eight pairs of tensiometers were installed at depths of 0.825 and 0.975 m within the experimental plot. During a 7-day period in August, 1995 the plot was sprinkler-irrigated on three days, and water application rates and uniformity coefficients were calculated for each irrigation event. Neutron probe readings at 15 cm depth increments and tensiometer readings were taken 4 to 6 times daily. Results showed large evaporation losses during and immediately after the irrigations. Evaporation losses of the wetted area was estimated to be between 2 and 4 mm/irrigation event. Consequently, application efficiencies were only 73–79%, the wetting of the root zone was limited to the 0–30 cm depth interval only, the soil profile was depleted of soil water, and daily crop coefficient values at days between irrigation events were between 0.6 and 0.8. The study recommends irrigation in the evening and night hours, thereby

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largely eliminating the evaporation losses that occur during daytime irrigation hours.

Keywords: Irrigation water management; Irrigation efficiency; Crop coefficient

1. Introduction

Micro-irrigation offers a large degree of control of water application to meet water requirements of trees. Irrigation scheduling of micro-irrigation systems is usually based on a water budget method to maintain a favorable soil water content status in the root zone, i.e., to minimize periods of water stress and leaching below the root zone. However, for localized micro-irrigation systems, it is difficult to evaluate the various terms of the water balance. Detailed soil water monitoring is necessary to obtain accurate estimates of actual tree water use.

A field study was initiated to evaluate the use of micro-sprinklers for irrigation of almond trees. This study was part of a larger on-project which is evaluating the physical performance of various micro-irrigation systems (Schwankl et al., 1996).

Micro-sprinkler irrigation has the advantages of drip irrigation, but irrigation water is applied over a surface area larger than under drip irrigation. Consequently, the root system is distributed within the larger wetted soil volume, thereby making available a larger reservoir for plant nutrients and water which may be needed in high water demand periods. Moreover, most of the active roots will develop in the upper soil layers where the organic matter content is at a maximum (Dasberg et al., 1985; Hamer, 1987; Kjelgren et al., 1985; Meyer and Peck, 1985; Roth and Gardner, 1985). Micro-sprinkling is particularly suitable for soils with low permeability and small soil water storage, or on hill slopes where runoff might occur. As with drip irrigation systems, micro-sprinklers are designed for high frequency irrigation and application rates can be controlled to minimize surface ponding. Moreover, the larger wetted area of the micro-sprinkler precludes the formation of localized salinity accumulation, whereas salinity levels are typically low near the soil surface and increasing with depth. Disadvantages of micro-sprinklers are associated with water losses due to wind effects and evaporation. Micro-sprinkler distribution uniformity has also been of concern since micro-sprinklers tend to have poor application uniformity over their wetted area.

Nevertheless, studies with different types of micro-sprinklers (Goldhamer et al., 1985; Klassen, 1986; Post et al., 1984 Post et al., 1985, 1986; Renn, 1986) have shown a uniform soil water distribution in the root zone. Thus, the low application uniformity does not necessarily affect the spatial distribution of tree roots and the corresponding root water uptake (Boman, 1991; Meyer and Peck, 1985).

From the few data available to date, it is clear that more research is needed to better understand irrigation response of tree crops (Fereres and Goldhamer, 1990), especially in partially wetted soils as occur under drip and micro-sprinkler irrigation. The objective of this study is to estimate the daily water balance for an almond tree in an orchard using micro-sprinkler irrigation. Daily water application uniformity and application efficiency of the micro-sprinkler system were also evaluated, taking into consideration water losses by soil evaporation.

2. Material and methods

The study was conducted during the summer of 1995 in a 6-yr-old almond orchard (Nickel's Ranch), located 90 km north of Davis, CA, in the Sacramento Valley. Tree spacing was 4.8 m × 6.6 m. Soil water was monitored around a single almond tree of the Butte variety, grafted on a 'Lovell Peach' rootstock. The soil surface between trees was maintained free of weeds by periodic herbicide treatment. The orchard had not been tilled since tree establishment in 1990.

The majority of soils at the Nickel's Estate Marine Ave. orchard are classified as an Arbuckle series, with soil porosity decreasing with depth and restricted internal drainage as caused by a clayey substratum (Harradine, 1948). The shallow soil contains substantial gravel, which in combination with the high sand content causes a low water holding capacity. Particle size distribution, bulk density and gravel content (kg gravel/kg soil) are listed in Table 1. Soil textural data were averaged values from six replicates. The reported bulk density and gravel content values represent their average values from eleven 61.5 cm^3 soil samples. Gravel density was measured by volume changes of submerged gravel in a graduated cylinder, while correcting for possible water inhibition by the gravel. The small size of the bulk density sampler limited the gravel size collected, and thereby biased gravel content and gravel density. The volumetric gravel fraction was computed from:

$$\phi_g = m_g\left(\frac{\rho_b}{\rho_g}\right), \tag{1}$$

where ϕ_g and m_g denote the volumetric (m^3 gravel/m^3 bulk soil) and mass gravel content (kg gravel/kg bulk soil), and ρ_b and ρ_g denote the soil's bulk density and gravel density, respectively.

The Nickel's Estate almond orchard is 8.8 ha large, one third of which is irrigated by micro-sprinklers (Bowsmith Fan-jets [1]), placed midway between trees in the tree row. The micro-sprinklers have a fixed head which produces 22 single streams of water in a full circle wetting pattern. Water is discharged through an orifice, impacting onto a horizontal plate, causing discharge of individual streams of water in a full circle pattern. At their operating pressure of 0.15 MPa, the micro-sprinklers have an average discharge of 41.7 l/h, and a wetted diameter of approximately 4.0 m. Specified flow rates are 35.2 and 45.4 l/h at operating pressures of 0.10 and 0.17 MPa, respectively, corresponding with wetted diameters of 3.6 and 4.2 m. A flow meter was installed in the lateral line which measured the cumulative flow rate of the micro-sprinkler of the instrumented almond tree along with nine other micro-sprinklers in the same lateral.

The experimental plot covers about one quarter of the wetted area of one micro-sprinkler, representing a single tree. In the 2.0 m × 2.0 m monitored area, 25 PVC neutron probe access tubes (diameter of 50 mm) were installed in a square grid of 0.50 m spacing to a depth of 90 cm (Fig. 1). In addition, eight pairs of tensiometers were installed in a regular pattern between the access tubes at depths of 82.5 and 97.5 cm,

[1] Bowsmith, P.O.Box 428, Exeter, CA 93221, USA.

Table 1
Particle size distribution, dry bulk density and volumetric gravel content as a function of depth

Depth (cm)	Soil texture (%, by weight)			Bulk density, ρ_b (kg m^{-3})	Gravel content, m_g (kg kg^{-1})	Gravel density, ρ_g (kg m^{-3})	Volumetric gravel content, ϕ_g (m^3/m^3)
	Sand	Silt	Clay				
15				1598	0.27	1750	0.25
30	53.0	41.0	6.0	1610	0.33	1830	0.29
45				1646	0.30	1700	0.29
60	58.0	32.5	9.5	1738	0.43	1860	0.40
75				1807	0.30	1750	0.31
90	67.0	25.0	8.0	1790	0.30	1800	0.30
105					0.39	1940	
120					0.48	1890	

respectively. This 4-m^2 area approximates one quarter of the wetted area of a single almond tree. However, the neutron probe and catch can measurements were assumed to represent a 2.25 m × 2.25 m (5.0625 m^2) area, taking into consideration the additional area represented by the measurements of the southern and eastern boundary of the experimental area. Since water application rates were low, there was no evidence of the experimental layout affecting the soil water regime, as caused by the large number of neutron probe access and tensiometer tubes within a relatively small area. The micro-sprinkler in Fig. 1 is located at the origin, whereas the almond tree is 2.4 m away from the micro-sprinkler. The neutron probe was calibrated from gravimetric measurements using soil samples collected at depths of 15, 30, 45, 60, 75 and 90 cm below the soil

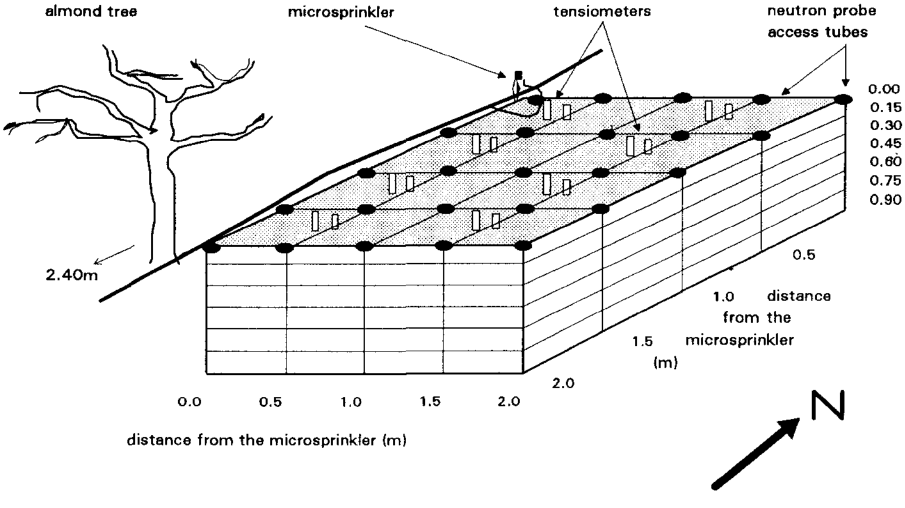

Fig. 1. Schematic of experimental plot.

surface during the access tube installation, as well as from samples collected nearby the access tubes after their installation. Separate calibration curves were used for the 0–15 cm surface soil, the 30–60 cm soil depth interval and the 75–90 cm soil depth. Standard errors of estimate of volumetric water content using these three calibration curves were approximately 0.01 (15 cm depth) and 0.02 m^3 m^{-3} (all other measurement depths). Soil water pressure readings were taken by a Tensimeter [2] pressure transducer type.

The leaching rate below the 90 cm depth was estimated using the soil water pressure and water content measurements, in combination with the unsaturated hydraulic conductivity function of that depth, as reported by Andreu et al. (1997). After linear interpolation of the tensiometric data across the experimental plot, vertical water fluxes were evaluated for all neutron probe access tube locations.

In the period 8/18–8/25/95, the experimental plot was irrigated three times (8/18, 8/21, and 8/23). During each of these water applications, the water application distribution was measured by catch cans, placed on top of each of the 25 neutron access tubes. Catch cans were 96 mm in diameter and 65 mm high. Using the catch can readings, the micro-sprinkler application rate was measured for one hour periods (3 to 7 times) during each of the three irrigations. The catch cans were emptied near the measurement location which they represented. Coefficient of variation (CV), Christiansen uniformity (CU) coefficient (Christiansen, 1942), and distribution uniformity (DU, average low-quarter amount of water caught to the plot-average amount of water caught) were computed to estimate application uniformity for each 1-h measurement, each irrigation event and for the three irrigations combined. The CU-values were computed from:

$$\mathrm{CU} = 100\left(1.0 - \frac{\Sigma X}{nm}\right), \tag{2}$$

where X denotes the absolute deviation of the individual observations from the mean, n is the number of observations and m is the mean depth of water application. Applied water as measured with the catch cans was compared with the meter readings in the irrigation lateral of the experimental plot.

The amount of water applied was based on California Irrigation Management Information System (CIMIS) data (Snyder et al., 1987). No rain was recorded during the measurement period and the application rates were based on the estimated crop evapotranspiration (ET_c,), which was calculated from:

$$ET_c = K_c \cdot K_r \cdot ET_0, \tag{3}$$

where K_c denotes the crop coefficient, and K_r equals the reduction coefficient taking into account the percentage of soil surface covered by the crop canopy as compared with total surface area. ET_0 is the potential evapotranspiration as estimated using atmospheric data from the nearest meteorological CIMIS station (Station No. 27, Zamora, CA). Goldhamer and Snyder (1989) and Snyder et al. (1987) recommended values for K_c and K_r of 0.9 and 1.0, respectively, corresponding to conditions of 60% canopy coverage of

[2] Soil Moisture Systems, Las Cruces, NM.

the soil surface for drip-irrigated trees in the Sacramento Valley. Moreover, application efficiency was assumed to be 90%.

In addition to soil water pressure and water content measurements, which were taken before and after every water application, neutron probe and tensiometer readings were taken daily at about 0600, 1000, 1400, and 1800. Moreover, readings were taken daily at 2200 and 0200, after the first water application only. The water balance was computed for each time interval, as well as on a daily basis. Soil water storage was computed for the 0–22.5, 22.5–37.5, 37.5–52.5, 52.5–67.5, 67.5–82.5, and 82.5–97.5 cm soil depth intervals, corresponding to the 15, 30, 45, 60, 75, and 90 cm depth measurements of the neutron probe.

3. Results and discussion

3.1. Soil characterization

Soil bulk density values increase with depth from about 1600 near the soil surface to 1800 kg m^{-3} at the 75–90 cm soil depth (Fig. 2). The mass distribution of gravel

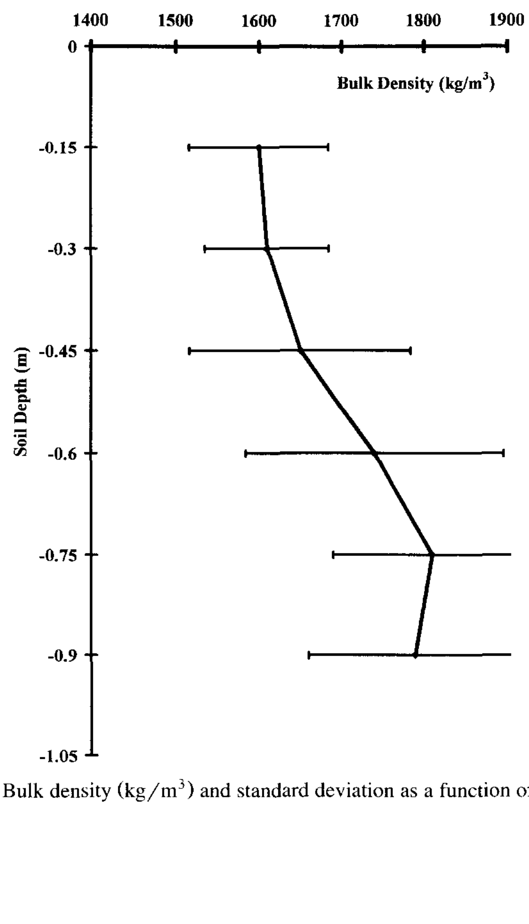

Fig. 2. Bulk density (kg/m^3) and standard deviation as a function of depth.

corresponds to a volumetric gravel fraction of between 0.25 and 0.40 m^3 m^{-3}. While assuming a negligible gravel porosity, these high gravel contents limit the total soil porosity from 0.30 m^3 m^{-3} near the soil surface to about 0.24 m^3 m^{-3} at the lower soil depths. This, together with the high silt content, explains the low saturated hydraulic conductivity of 0.005 m/h (Andreu et al., 1997) at the 90 cm soil depth, and confirms the conclusion of Harradine (1948) of restricted internal drainage.

3.2. Application uniformity

Application uniformity by the micro-sprinklers was characterized by the Christiansen uniformity (CU) coefficient, the distribution uniformity (DU), and the coefficient of variation (CV). These parameters are listed in Table 2, together with application amounts (l and mm) and application rates (mm/h) for each of the three irrigations of the experimental plot.

The irrigation application amounts, as estimated from the catch can readings, compared favorably with those estimated from the flow meter. This flow meter monitors the total flow to the 10 micro-sprinklers in the lateral of the experimental plot. The agreement between the two irrigation amount estimates is excellent for the second irrigation event (8/21, Table 2), when the wind speed was lowest during the irrigation period. The smaller applied water values as estimated from the catch can readings in 8/18 and 8/23 can be attributed to some evaporation losses as the water moves through the air. For example, the estimation of evaporation of Yazar (1984) losses by sprinkler irrigation was between 1 and 17%, with evaporation losses positively correlated to higher wind speeds and lower air humidity values. Also, on days when wind speeds are high (8/18 and 8/23, Table 2), a fraction of the applied water may drift from the experimental plot, thereby reducing the volume of water that is applied to the experimental plot as compared with the flowmeter discharge. However, observations showed the radius of the wetted area to be mostly smaller than 2.25 m. The potential for evaporation losses in the air and wind drift together could explain the higher water application amount as estimated by the flow meter as that measured by the catch cans on 8/18 and 8/23, whereas excellent agreement between the two measurements was found on 8/21 when the wind speed was the lowest during the experimental period. Differ-

Table 2
Applied water (l and mm) and application uniformity (CU, DU and CV) for the 2.25 m × 2.25 m experimental plot for each irrigation event in the 8/18–8/23 experimental period

Date	Applied water [l (mm)]		Application rate (mm/h)			Application uniformity (%)		
	Catch cans	Flow meter	Mean[a]	SD[a]	Mean[b]	CU	DU	CV
8/18 (13.5)[c]	116 (22.9)	125 (24.7)	1.70	1.07	1.83	45	23	63
8/21 (7.5)	86 (17.0)	85 (16.8)	2.27	3.10	2.24	−9	2	136
8/23 (9.0)	90 (17.8)	106 (20.9)	1.98	1.81	2.32	25	17	91
8/18–8/23 (30.0)	292 (57.7)	316 (62.4)	1.98	1.58	2.08	35	31	79

[a] Mean and standard deviation of water application rate from catch can readings.
[b] From flow meter data.
[c] Duration of irrigation (h).

ences in applied water between the catch can readings and the flow meter can also be partly attributed to differences in emission uniformity (EU) between micro-sprinklers. Schwankl et al. (1996) measured an EU of 91%, corresponding with a emitter discharge varying between 38 and 48 l/h. The flow meter readings indicated that mean water application rates varied between 1.83 and 2.32 mm/h between irrigations. There is no explanation for the variation in mean application rate between the three irrigation events, other than it is caused by fluctuations in water pressure in the irrigation system. The standard deviation in water application rate is highest on 8/21, when the wind velocity is lowest.

The reported CU and DU values are extremely low, with their lowest measured during the second irrigation (CU = −9% and DU = 2%), when four of the catch cans at the southern boundary of the experimental plot did not receive any irrigation water. Although the wetted radius of the micro-sprinkler was about 2.0 m, all catch cans within the 2.0 m × 2.0 m instrumented area received water during the two other irrigation events. For the most part, it was concluded that the low application uniformity was caused by the type of micro-sprinkler, distributing its water by individual streams of water, and to a much lesser extend by wind drift. In fact, the application uniformity increased as the wind speed increased (Table 3) by the shifting wind directions during water applications thereby changing water application patterns. When integrated over time, the multiple irrigations resulted in a water application distribution with a CU and DU of 35 and 31%, respectively. The patterns of irrigation water distribution can be easily distinguished in Fig. 3a–d, and they show the maximum average water application rate in the center of the experimental plot for two of the three irrigation events.

3.3. Soil water redistribution

In addition to the calculation of CU and the coefficient of variation (CV) of the applied water at the soil surface, water uniformity characteristics were also estimated for soil water storage at successive depths and compared with that of the soil surface applications. CU and CV for all 25 neutron probe measurement locations were computed from the deviations of soil water storage relative to the mean soil water storage for each depth increment for each measurement time. The results are presented in Fig. 4. Irrigation applications started at 0, 72, and 120 h. Rather unexpectedly, the CU of the first soil layer immediately after the irrigations is already much higher (larger than 70%) than any of the soil surface water application uniformities. Part of this increase in uniformity is attributable to the larger measurement sphere of influence of the neutron probe (radius between 10 and 20 cm) as compared to the 72.4 cm^2 area represented by a single catch can. Fig. 4 clearly shows the drop in CU (and rise in CV) immediately after the second and third irrigation, and a gradual improvement in their values for both the 0–15 cm and the 15–30 cm depth increments as time progresses. Uniformity values for the other depth increments do not seem to be affected by the irrigation applications, indicating that the soil is not wetted beyond the 30 cm depth. Apparently, the low water application uniformity at the soil surface is of little influence on the spatial soil water distribution. Applied irrigation water is rapidly redistributed in the soil by soil water potential gradients. Moreover, we hypothesize that water extraction by tree roots further

Table 3

Water balance (mm) for 0.975 m soil profile with derived application efficiency (E_a) and crop coefficient (K_c) values for 8/18–8/24 experimental period, and selected meteorological data. Soil water storage measurements were taken at 6 AM, the following day

	Observation date								
	8/17	8/18	8/19	8/20	8/21	8/22	8/23	8/24	8/17–8/24
$I_{applied}$ (mm)[a]		22.9			17.0		17.8		
$I_{applied}$ (mm)[b]		14.6			10.9		11.4		36.9
Water storage (mm)[a]	129.2	136.0	129.6	123.1	127.0	121.1	124.6	119.5	
Change in storage (mm)[a]		6.8	−6.4	−6.5	3.9	−5.9	3.5	−5.1	
Change in storage (mm)[b]		4.35	−4.1	−4.2	2.5	−3.8	2.23	−3.3	−6.3
ET_0 (mm)[c]		6.3	5.8	6.1	5.5	5.1	6.8	5.6	41.2
ET_c (mm)[b]		6.3	4.1	4.2	5.5	3.8	6.8	3.3	
I_{soil} (mm)[b,d]		10.65			8.0		9.03		27.7
Water application efficiency (E_a)[e]		0.73			0.73		0.79		0.75
$K_c^* K_r^f$		1.0	0.71	0.69	1.0	0.77	1.0	0.59	1.05
24-h T_{max} (°C)		33	34	37	37	35	38	32	
24-h T_{min} (°C)		14	12	15	16	16	17	14	
Maximum relative humidity (%)		66	80	68	79	92	81	80	
Minimum relative humidity (%)		18	19	21	21	36	19	23	
Average wind speed (m/s)		2.0	1.2	1.6	1.6	1.5	2.7	2.2	

[a] Wetted area = $4(2.25 \times 2.25) = 20.25\ m^2$.
[b] Total area = $4(2.4 \times 3.3) = 31.67\ m^2$.
[c] ET_0 = Reference ET.
[d] I_{soil} = Change in water storage + ET_0.
[e] $E_a = I_{soil} / I_{applied}$.
[f] $K_r = 1.0$.

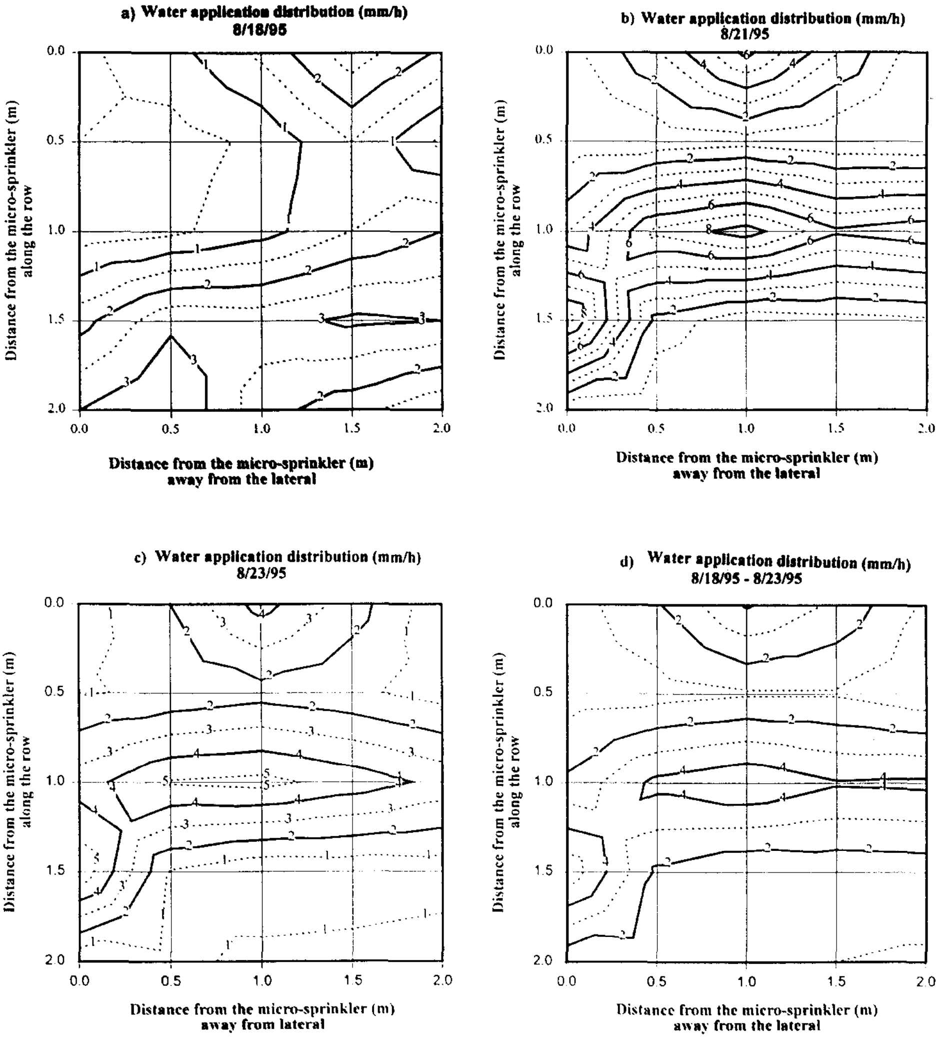

Fig. 3. Variation in sprinkling rate (mm/h) for experimental plots as determined from catch can readings for (a) 8/18, (b) 8/21, (c) 8/23 and (d) the three irrigation events combined. Values are averaged for each irrigation event.

increased soil water uniformity as time proceeds. This conclusion corresponds with the results of previous studies (Goldhamer et al., 1985; Koumanov, 1994; Post et al., 1985).

To better understand the relationship between the amount of applied water and the amount of water stored in the soil profile, Fig. 5 presents these two variables for each measurement point and water application (Fig. 5a–c), as well as for all three applications combined (Fig. 5d). Each data point represents the volume of water (l) applied as computed from a catch can reading and the volume of water (l) added to the soil as

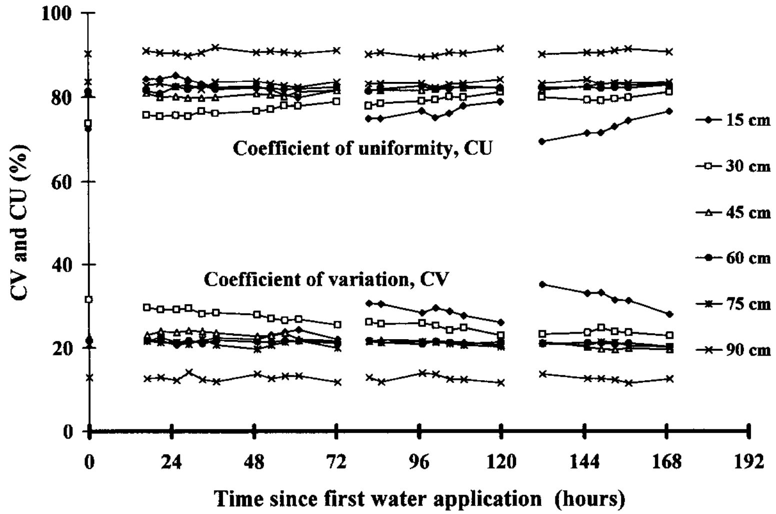

Fig. 4. Coefficient of variation, CV (%), and coefficient of uniformity, CU (%), of soil water content as a function of time and depth for the period 8/18–8/25/95.

estimated from neutron probe readings to the 90 cm depth, before and immediately after each irrigation. The values were determined assuming that the representative areas for both the catch can and neutron probe measurements were equal. Water balance calculations were simplified because of the absence of significant drainage during and between irrigations. Estimated drainage rates were insignificant because of the small soil water potential gradients and corresponding low soil hydraulic conductivity values at the bottom of the root zone. First, it is noted from Fig. 5 that the correlation coefficient R decreases as the CU of the soil surface water application decreases. For example, the R^2-values decreases from 0.77 (in 8/18) to 0.36 (in 8/21) as the DU decreases from 23 to 2%. Thus, as the nonuniformity of soil surface water applications increases, the smaller catch cans are less representative of the larger-scale neutron probe measurements. Second, the average slope of the regression lines is about 0.33, indicating that the plot-average net increase in soil water storage by irrigation is only approximately one third of the applied irrigation water. Since irrigation events last between 7.5 and 13.5 h and take place during the day, differences between the amounts of water applied and water stored are expected to occur because of tree transpiration through root water uptake as water is applied. However, as will be shown later, these differences are much larger than can be explained by transpiration alone.

3.4. Water balance calculations

Using the water applications amounts as estimated from the catch can readings (Table 2) and soil water storage changes from the neutron probe measurements, daily water balance calculations yielded actual daily evapotranspiration ET_c-values (Table 3). Daily

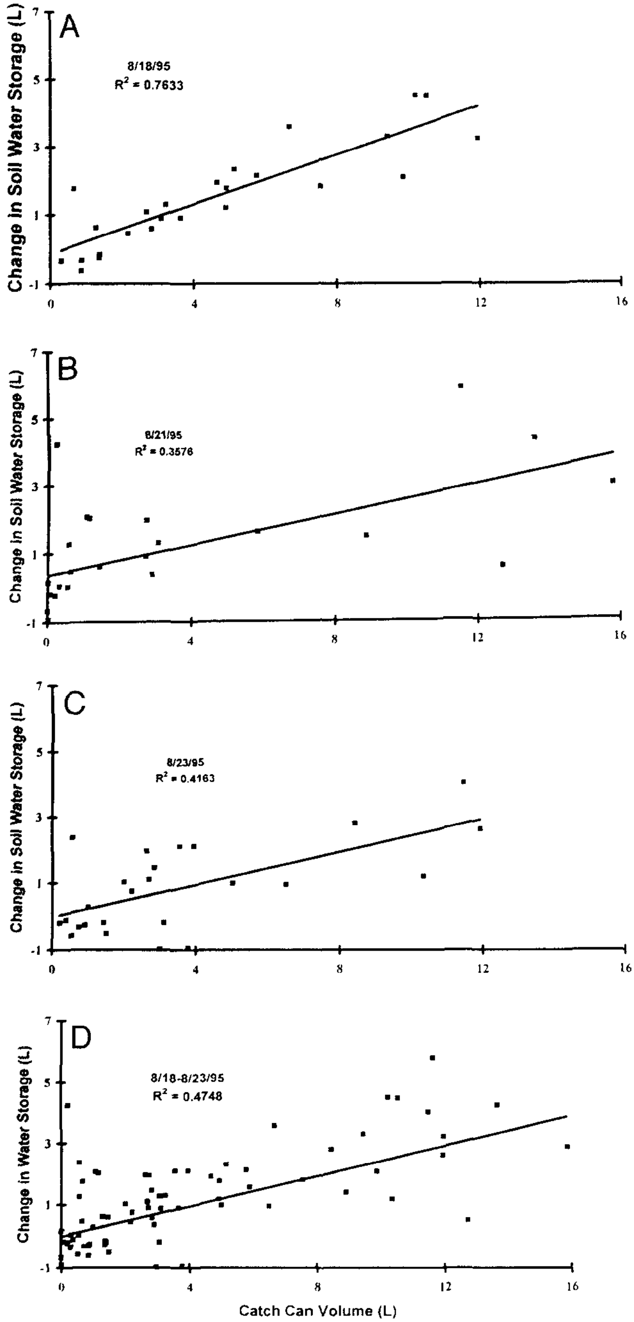

Fig. 5. Correlation between the volumes of applied water (catch cans) and the change of soil water in the root zone (neutron probe measurements) for (a) 8/18, (b) 8/21, (c) 8/23 and (d) the three irrigation events combined.

changes in soil water storage were computed from the daily 6 AM neutron probe measurements. In these calculations, the leaching component in the total water balance was negligible. In fact, net vertical flux at the bottom of the root zone (90 cm depth) for the wetted area was upward, with estimated daily values of 0.02, 0.2, 0.3, 0.4, 0.4, 0.4 and 0.3 mm, respectively, during the 8/18–8/24 experimental period. Since neutron probe and water application data were collected from the 2.25 m × 2.25 m experimental area, water balance calculations were applied to that wetted area only. As demonstrated by Andreu et al. (1997), the volumetric water content of the non-irrigated 2-m wide strip between the tree rows is decreased to about 0.10 m^3 m^{-3} or less at the conclusion of the irrigation season. Therefore, the assumption of negligible root water uptake from this strip of soil is valid. In order to compare estimated ET values with those recommended using CIMIS data (ET_0), actual ET (ET_c) was corrected for the total tree area (31.67 m^2).

For each of the three water application days (8/18, 8/21 and 8/23), the water application efficiency (E_a) was defined as the ratio of the estimated amount of water entering the soil to the applied amount of water, i.e., $E_a = I_{soil}/I_{applied}$, thereby assuming that tree water use is equal to the reference ET (ET_0) on the days that water was applied, so that I_{soil} was estimated from the sum of ET_0 and change in water storage. Thus, in applying the water application efficiency concept for our situation, the differences between the amount of water applied and water entering the soil are considered losses, resulting in water application efficiency values between 73 and 79%. For the days between irrigations (1/19, 8/20, 8/22, and 8/24), the water balance was used to estimate the actual daily crop coefficient (K_c), assuming that $K_r = 1.0$. K_c-values for those days varied between 0.59 and 0.77, with the lowest value at the last day of the experimental period. Estimated daily crop coefficient values correspond well with those determined by Andreu et al. (1997) for the drip-irrigated almond trees.

The water losses on the irrigation days are explained by the high temperature, low air humidity and average wind speed (Table 3), as well as by advective heat moving from the dry soil strips between trees to the wetted areas along the tree rows, thereby exceeding ET_0. On all days, irrigation started at around 6 AM and lasted for 7.5 to 13.5 h. We hypothesize that these conditions led to enhanced evaporation of the wetted soil surface, relative to reference crop ET. The presented situation is similar to evaporation from a water surface that occurs in evaporation pans placed in dry fallow areas for which pan coefficients of 0.55–0.75 were measured (Doorenbos and Pruitt, 1977). Thus, we conclude that a significant portion of the micro-sprinkler applied water is lost by evaporation from the wetted soil surface. The partioning between E and T of the additional energy by advective heat transport is uncertain, but it is likely that not all energy is used by evaporation only (Fereres et al., 1982). Water losses could be significantly reduced if the micro-sprinkler system was operated during the night when temperatures are much lower and relative humidity is high (Table 3). A water balance calculation for the combined 7-day period (last column of Table 3) resulted in a cumulative actual ET-value (ET_c) of 43.2 mm ($I_{applied}$-change in water storage = 36.9 + 6.3 mm), yielding a crop coefficient of 1.05. Thus, weekly water balance measurements overestimate water use by transpiration and crop coefficient values since evaporation losses will be neglected on days when water is applied.

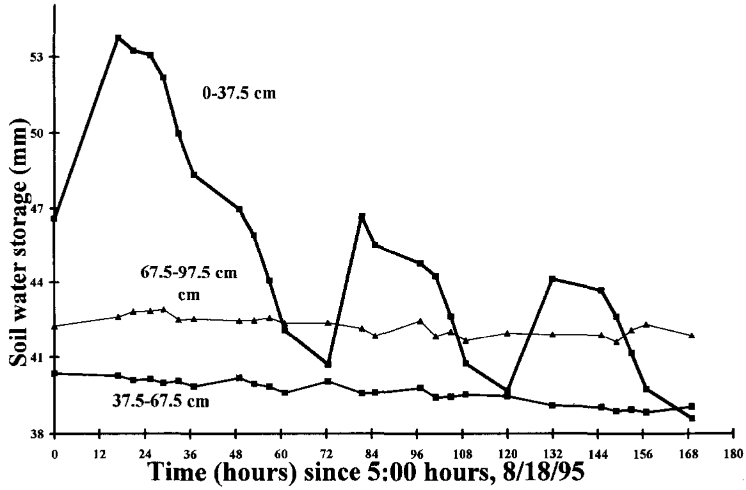

Fig. 6. Change in soil water storage (mm) as a function of time for soil depth intervals of 0–0.375 m, 0.375–0.675 m, and 0.675–0.975 m.

Fig. 6 shows that the water applications only increased soil water storage in the upper 0–37.5 cm of the soil. Root water uptake occurred in this surface layer only, with the deeper soil layers not changing in soil water content during and between water applications. The limited extend of the active root zone was due to high frequency

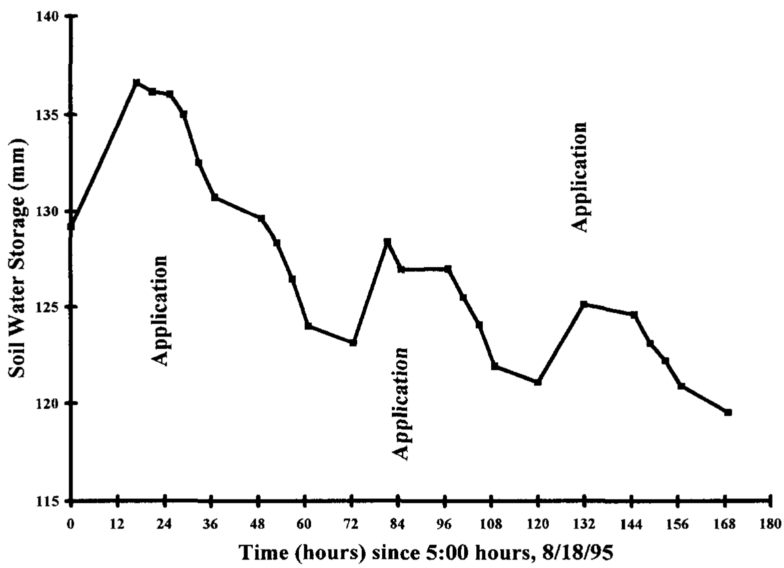

Fig. 7. Change in soil water storage as a function of time for 0–0.975 m soil profile.

irrigation, with the applied water only wetting the 0–37.5 cm soil layer. The soil water storage data in Figs. 6 and 7 represent soil water storage data for the 2.25 m × 2.25 m plot area.

Because of the limited net increase in soil water storage after the water applications (Table 3), estimated evapotranspiration during the days without irrigation is lower than reference ET. As is shown in Fig. 7, the soil water storage steadily declined from 129.2 mm (8/17) to 119.5 mm (8/24, after 168 h), leading to a profile-average volumetric water content in the wetted area of about 0.125 m^3 m^{-3} only. Evapotranspiration rate (mm/h) for the 31.67 m^2 tree area as a function of time is presented in Fig. 8. Clearly shown are the initially high ET-rates during the water applications as caused by surface evaporation of applied water, and the diurnal fluctuations with rates peaking in the afternoon, and decreasing to near zero during the night hours.

The experimental data show that for conditions of high temperatures and low air humidity, the targeted water application amounts must be augmented to compensate for evaporative losses during micro-sprinkler irrigation. This means in practice that corrections to the irrigation efficiency values must be determined which account for such evaporation losses. Of course, the immediate solution is to irrigate during night time hours when the meteorological conditions are much more favorable. As Table 3 shows, night time temperatures were much lower and air humidity values higher than during the day time. However, as was demonstrated by Even-Chen et al. (1981), night time irrigation would prevent the potential beneficial effects of daytime irrigation by reducing heat stress.

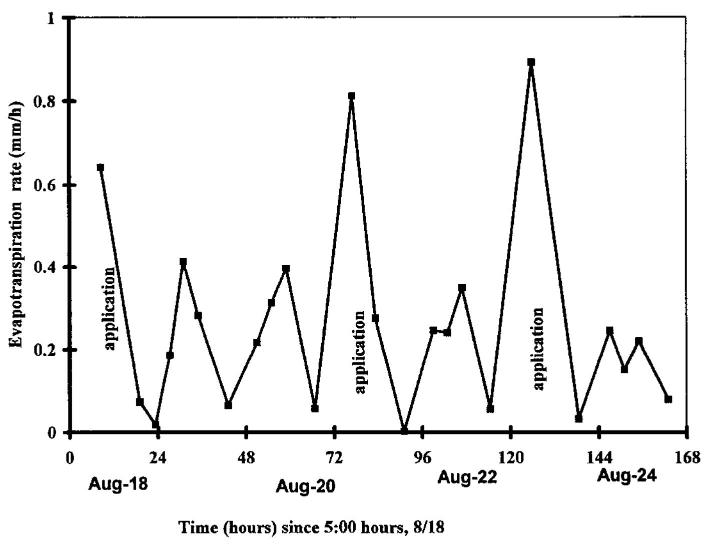

Fig. 8. Evapotranspiration rate (mm/h) for almond tree as estimated from water balance calculations.

4. Conclusions

Although micro-sprinklers produced a highly variable soil surface water application distribution within the wetted area of the tree, soil water uniformity as estimated from neutron probe measurements was high. Most likely, irrigation water is rapidly redistributed by soil water potential gradients, whereas root water uptake provides a mechanism to reduce soil moisture variability. Water application uniformities increased on days with higher wind speeds, indicating that the low water application uniformity was caused by the sprinkler pattern of the micro-sprinklers.

Results showed that water application efficiency was about 73–79%. Water losses were due to evaporation of water from the wetted soil surface when water was applied. Consequently, soil water storage was depleted during the experimental period, possibly leading to water stress for the almond tree. This was confirmed by the estimated daily crop coefficients, whose values were much lower than suggested for irrigation scheduling. Using water balance calculations, daily crop coefficient values between irrigation events varied between 0.6 and 0.8, with the lowest value occurring at the end of the experimental period. Soil water storage measurements also showed that soil wetting of all water applications was limited to the surface 0–37.5 cm depth interval, which suggests that active root water uptake during the growing season occurred in the surface soil layer only. However, root excavations showed that roots extended to the 90–100 cm soil depth, indicating that the trees may extract soil water at larger depths after the winter rains in the early stages of the growing season.

The study concludes that significant water savings can be achieved if the micro-sprinkler irrigation system is operated during the evening and night time hours only, when air temperature is low and air humidity is relatively high as compared to day time hours.

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