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MICRO-IRRIGATION: ADVANCES IN SYSTEM DESIGN AND MANAGEMENT

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Water use by drip-irrigated late-season peaches

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Abstract A 4-year experiment was conducted using a large weighing lysimeter to determine the crop coefficient and crop water use of a late-season peach cultivar (*Prunus persica* (L.) Batsch, cultivar O'Henry) irrigated with a surface drip system. Two trees were planted in a 2×4×2 m deep weighing lysimeter that was surface irrigated with ten 2 L/h in-line drip emitters spaced evenly around the trees. Irrigation was applied in 12 mm applications after a 12 mm water loss threshold was exceeded as measured by the lysimeter. The crop coefficient (K_c) was calculated using the measured water losses and grass reference evapotranspiration calculated using the CIMIS Penman equation. K_c was plotted against day of the year and linear, quadratic, and cubic regressions were fitted to the data. A three-segment linear and the cubic equation had the best fit to the data. The maximum K_c determined for the linear fit in this experiment was 1.06 compared with a maximum of 0.92 recommended for use in California and 0.98 calculated using the FAO method. Average annual water use for the 4 years of the experiment was 1,034 mm. Mid-day canopy light interception was found to be well correlated with the crop coefficient determined using the lysimeter data.

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Introduction

Accurate irrigation scheduling is needed to match the depth of application to the crop water requirement. Proper irrigation scheduling requires actual crop water use data in relation to the potential water use (evapotranspiration) as a function of plant development. The data for the water requirements of deciduous fruit and nut crops as a function of growth varies widely depending on climate, soil, and irrigation methods and management. As a result, they are difficult to interpret and not necessarily useful for establishing baseline values. The relationship between crop water use and potential water use is often called the crop coefficient. These data are routinely collected for field crops using drainage and weighing lysimeters but seldom for tree crops because of the large lysimeters required and the need to collect data over several years. Water use data for perennial crops have often been collected in the past using soil water balances for short periods of time, which is not a very accurate method (Fereres and Goldhamer 1990). Various studies, using this method and weighing and drainage lysimeters, have produced widely varying crop coefficients for mature trees (Miyamoto 1983; Worthington et al. 1984; Mitchell et al. 1991; Chalmers et al. 1992). A large weighing lysimeter was constructed specifically to quantify the water requirements for an irrigated late-season peach variety, and to develop a crop coefficient to describe the crop water use as a function of time for a mature tree. Additional studies correlated the crop coefficient of mature trees with mid-day canopy light interception. This paper reports on the measured crop water use and the resulting crop coefficient for a well watered, mature, late-season peach variety based on lysimeter measurements and light interception.

Materials and methods

An experiment was conducted using a 1.0 ha (120×87 m) plot containing a weighing lysimeter located at the University of

California Kearney Agricultural Center in the San Joaquin Valley (SJV) of California (36°48′ N, 119°30′ W). The area surrounding the lysimeter was planted in 1988 to a late-season peach (*Prunus persica* (L.) Batsch, cultivar O'Henry) using a 1.8 m in-row spacing and a 4.9 m between-row spacing. Two trees were planted 1.8 m apart in the weighing lysimeter. The trees were trained to the Kearney Agricultural Center perpendicular "V" orchard system (DeJong et al. 1994). The experimental field was surrounded by a mixture of annual and perennial crops. The field was irrigated with fanjets, one per tree, while the trees in the lysimeter were surface drip-irrigated. The field was irrigated uniformly for the first 2 years for establishment. From the third year onward, the lysimeter was used to control irrigation on the field, beginning the first week in March at around the time of full bloom. A total of eight irrigation treatments with six replications in a randomized complete block design were used on the field. Each plot consisted of three rows of eight trees with the six trees of the middle row being the data sample trees. The trees in the lysimeter were fully irrigated and used to establish the water requirement for the peaches. The lysimeter was located in the center of a fully watered treatment plot and no edge effects were expected. The soil in the field is a Hanford sandy loam (typic xerothents) with approximately 400 mm of water available in a 3 m profile. Standard agronomic practices were applied to the crop each year including: annual dormant and midsummer pruning, hand thinning the fruit in April to achieve a given fruit count per tree, spraying for insects and disease, and fertilization with 50–100 kg/ha nitrogen. The mature trees were pruned to a height of approximately 3 m at the end of the growing season. Maximum height prior to pruning was approximately 4.5 m. Yields were determined by hand harvesting and weighing all fruit from each tree each year. Harvest dates ranged from 27 July to 19 August over the years of the study reported here. The soil under the trees was bare and the water use determinations will thus reflect both transpiration and evaporation. The resulting coefficient will be typical of water use by well-watered peaches irrigated with a surface micro-irrigation system.

The weighing lysimeter dimensions are 2×4×2 m deep. The tank is weighed using a balance beam and load cell configuration with most of the weight being eliminated using counter weights. The soil was excavated from the lysimeter site in eight layers and stockpiled for use in refilling the tank. Soil bulk density was measured between 0.3 and 1.8 m depth in the soil profile during excavation. The lysimeter tank was hand filled in 0.15 m layers and compacted to approximately the original bulk density (1.64 Mg/m^3). During filling, stainless steel fritted tubing placed at a spacing of 0.6 m was installed in a 2.4-mm-thick layer of diatomaceous earth at the bottom of the lysimeter to act as a drain. After planting, two neutron access tubes were installed in the lysimeter. Detailed description of the lysimeter construction can be found in Phene et al. (1991).

Trees in the lysimeter were irrigated using ten 2 L/h in-line drip emitters positioned in a circle around each tree to give a wetting pattern approximately equal to that of the fanjets in the remainder of the field. Irrigation water was supplied from two 300-L water tanks suspended on the weigh bridge supporting the lysimeters. This was done to ensure that the irrigation water was included as part of the lysimeter mass. The lysimeter was weighed hourly to determine the evapotranspiration of the two trees and the change in mass was compared with the 12 mm (96 L) threshold value of ET$_c$ loss (1 mm = 8 L for the two trees). When the threshold was exceeded, the lysimeter was irrigated. At midnight the water tanks were refilled; the inflow was measured with a flow meter and recorded electronically and the new lysimeter mass was used as baseline for the next day. A Campbell Scientific micrologger (21x) was used to monitor and control the system and to communicate with a computer at the Water Management Research Laboratory (WMRL). Data were downloaded to the WMRL computers for processing daily at midnight. Approximately 50% of the lysimeter surface was wetted by the drip lines; this is equal to 22% of the equivalent tree area in the field. The average number of irrigations per month was; March 0, April 10, May 24, June 32, July 40, August 37, September 24, and October 10.

Weather data were collected by the California Irrigation Management Information System (CIMIS), from an automated weather station located approximately 2 km from the site. The reference crop evapotranspiration (ET$_o$) was calculated using the CIMIS Penman equation developed for use in the CIMIS system (Pruitt and Doorenbos 1977). The ET$_o$ data were calculated on both an hourly and a daily basis. The summation of the hourly values of ET$_o$ were used with the summed hourly values of measured crop evapotranspiration (ET$_c$) to calculate the daily crop coefficient, K_c, as the ratio of ET$_c$/ET$_o$. The crop evapotranspiration measured by the lysimeters was adjusted to an area equivalent loss using the area occupied by an individual tree (8.92 m^2) in the field. It took approximately 3 years (1988–1990) for the peach trees to reach full canopy cover and come into production of approximately 59 Mg/ha. The water use data from 1991 to 1994 were used to characterize the crop water requirements including both transpiration and evaporation for mature trees and to calculate the crop coefficient representing both aspects of water loss. The lysimeter surface was covered with plastic several times during the 4-year study to attempt to quantify evaporation losses, but there was insufficient data to establish a base coefficient (Wright 1982).

Mid-day tree canopy light interception was measured within an hour of solar noon on a cloudless day every 3–4 weeks using an Accupar linear PAR ceptometer (Decagon Devices, Pullman, Wash.) from April or May to August or September of each year. The ceptometer was held at ground level facing straight up to take an individual reading. At least 50 readings were averaged throughout the entire ground area assigned to the tree. This value was divided by a full sun reading taken in an open area next to the orchard and subtracted from 1 to give the proportion of light interception by that tree. Light interception between measurements was linearly interpolated. For this analysis, only the dates between the first and last light interception measurements were used in each year. This gave a total of 574 daily data points.

Results and discussion

Daily crop reference evapotranspiration data calculated using the CIMIS Penman equation are plotted for all four years in Fig. 1. The data show that the climate in the SJV is quite consistent from year to year. It should be noted that from the end of May to September, there are insignificant amounts of rainfall or clouds in the San Joaquin Valley, which accounts for the uniformity of ET$_o$ on a monthly basis.

The monthly crop water use (ET$_c$) data as measured by the lysimeter are given in Table 1. The daily values of ET$_c$ are plotted in Fig. 2. The daily measured crop water use follows the same trend as shown in Fig. 1 for the reference evapotranspiration. Crop water use with time increased until peak water use occurred in July and August (DOY 200–240), a shift of approximately 1 month compared to the peak reference ET$_o$. The daily ET$_c$ data were higher in 1993 than in the other years. It is not apparent why this occurred. The ET$_o$ in 1993 was less than in 1992 and the same as 1991. All of the agronomic practices were similar between years, as was the yield. The irrigation frequency was approximately the same on a monthly basis in each year of the study.

The measured daily water use and calculated daily crop reference evapotranspiration were used to calculate a crop coefficient K_c. The daily data are plotted in Fig. 3 for all years from 1991 to 1994. There is an extended period of increase in the value beginning with irrigation

Fig. 1 Daily reference evapotranspiration (*ET$_o$*) for 1991–1994 in the San Joaquin Valley of California

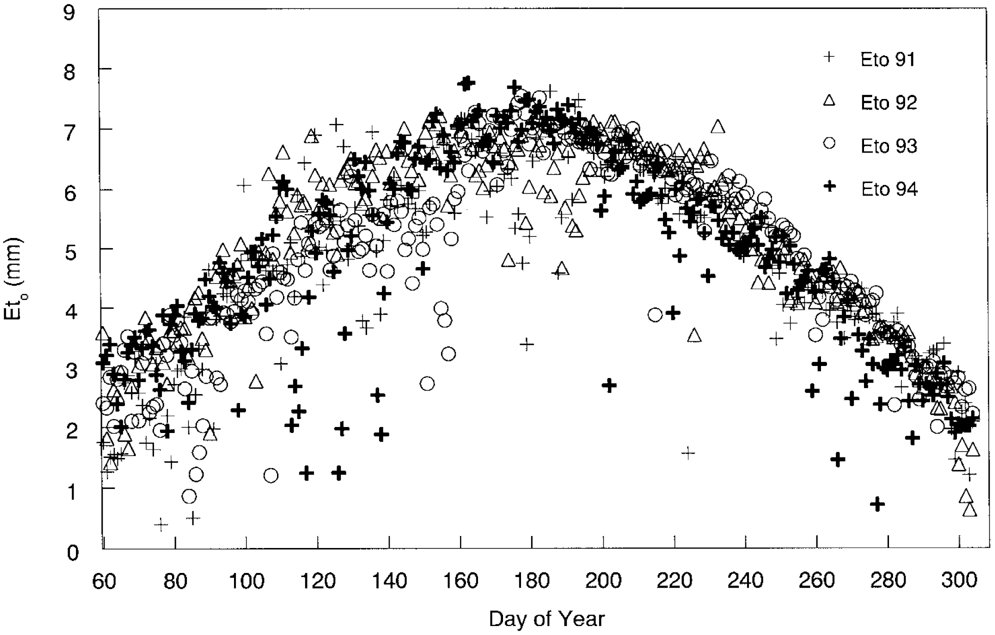
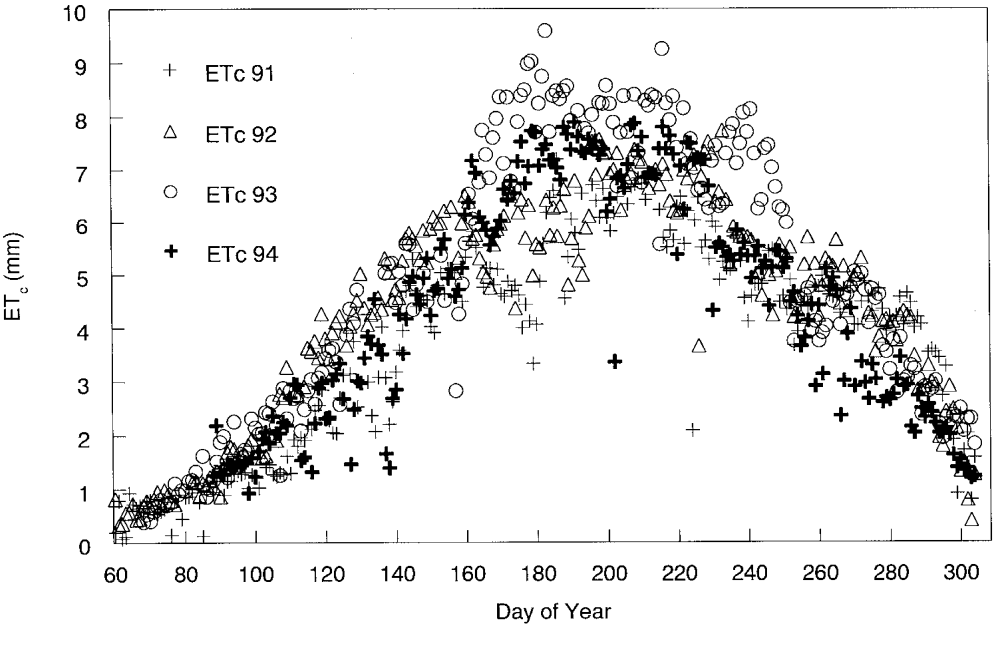


Table 1 Monthly water use of mature O'Henry peaches measured with a weighing lysimeter (L) and calculated (C) using the three-segment linear model based on the lysimeter data

Month	Water use (mm)							
	1991		1992		1993		1994	
	L	C	L	C	L	C	L	C
March	22	20	26	27	24	23	25	29
April	48	69	66	75	69	61	58	62
May	104	122	147	133	139	110	107	113
June	144	166	173	174	207	169	186	187
July	194	215	202	210	249	220	229	213
August	169	187	198	199	229	196	195	179
September	139	136	148	142	151	150	128	131
October	104	95	93	88	93	95	69	78
Total	927	1010	1053	1048	1161	1024	997	992

Fig. 2 Daily crop water (*ET$_c$*) use by O'Henry peaches measured with a weighing lysimeter



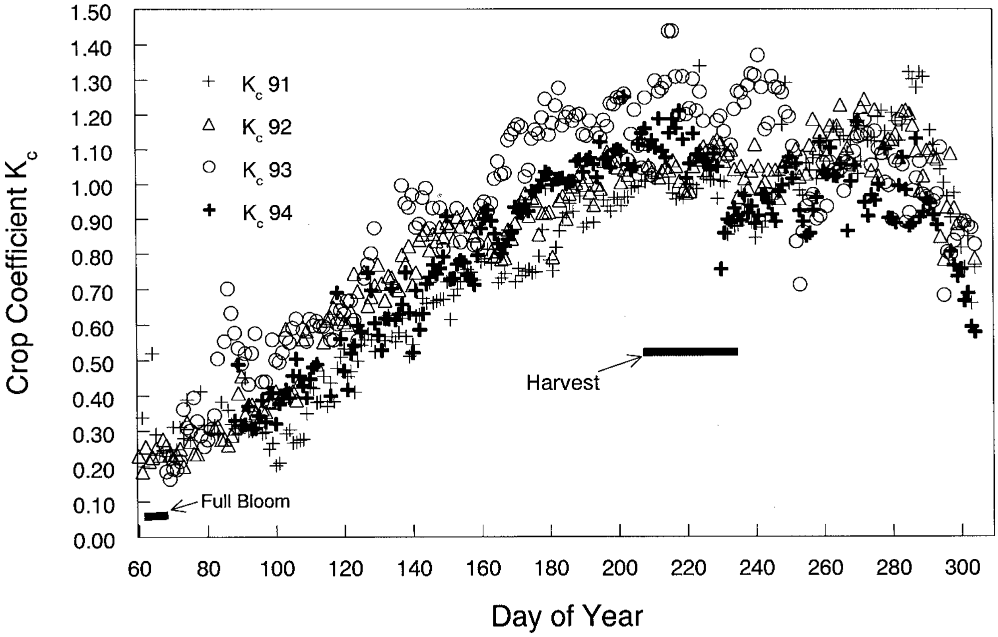


Fig. 3 Daily crop coefficient (K_c) for surface drip-irrigated O'Henry peaches in the San Joaquin Valley of California. *Bars* show range of dates for full bloom and harvest over the experimental period

in March and extending to early August (DOY 60–220). There is an apparent dip in the values at the end of August (DOY 240) with recovery in early September (DOY 250) followed by a rapid decline in October (DOY 280) when irrigation was ended. The periods of full bloom and harvest are shown in Fig. 3.

The dip at the end of August might reflect adjustments in tree water use in response to harvest. Researchers have reported increased water use with heavy fruit loads (Chalmers et al. 1983) so it would be reasonable to expect a decrease in water use after the fruit have been removed. However, the K_c values tended to return to preharvest levels by the end of September (DOY 250), so the postharvest dip was only temporary. Also, we generally observed (but did not quantify) some abscission of interior, shaded leaves immediately after harvest. Again, it might be expected that whole tree transpiration would be decreased by the abscission of these leaves, although the degree would depend on light interception and energy balance factors. Leaf area index (LAI) was not measured during this period, but light interception was measured. There were no measured differences in light interception during the period following the dip, suggesting that the changes in LAI were not responsible for the dip. More detailed studies are needed to determine the physiological factors that may be affecting tree water use during and shortly after fruit harvest.

The daily K_c values for each year were averaged and used for the analysis to determine a single crop coefficient as a function of day of the year. Regression analysis was used to fit linear, quadratic, and cubic equations to the daily K_c data as a function of the day of the year. The cubic term was found to be significant and thus represented a statistically better fit than the quadratic equation. The linear regression was patterned after the technique for determining crop coefficients described in FAO Irrigation and Drainage Paper 56 (Allen et al. 1998). Straight-line segments were fitted to the data and breaks in the curve occur at times having a physiological significance. This method is also used by the Cooperative Extension service of the University of California to develop crop coefficients for crops grown in California (Snyder et al. 1989).

In this study, the graph was broken into three time periods as follows. First, all the data were selected, beginning when K_c first equaled or exceeded 1.0 to when it was less than 1.0. These data were used to compute an average (1.06) which corresponds to the mid-season value in the FAO method. We established the length of this period as the day that $K_c \geq 1.06$ to the last day that $K_c \geq 1.06$. Then a linear regression fit was made to the data from day of the year 60 to the first day of $K_c \geq 1.06$. This time period represented the rapid growth period. The beginning of the flat peak K_c period corresponds to the termination of shoot growth. Even though it was not measured in this experiment, other studies of O'Henry shoot growth in the SJV of California show termination of shoot growth to occur in mid-July (DOY 190–200) (DeJong et al. 1987). The late-season linear relationship was fitted to data from the last day $K_c \leq 1.06$ to the cessation of irrigation in mid-October (DOY 285–295).

Each regression equation is plotted in Fig. 4 along with the average K_c data. The crop coefficient for deciduous fruit trees recommended for use in the Cooperative Extension bulletin (Snyder et al. 1989) is also plotted on Fig. 4. For purposes of comparison, the K_c curve was developed using the FAO method. We assumed a 1 March (DOY 60) green-up date. The mid-season value was adjusted to account for bare soil, a minimum relative humidity of 28%, and a tree height of

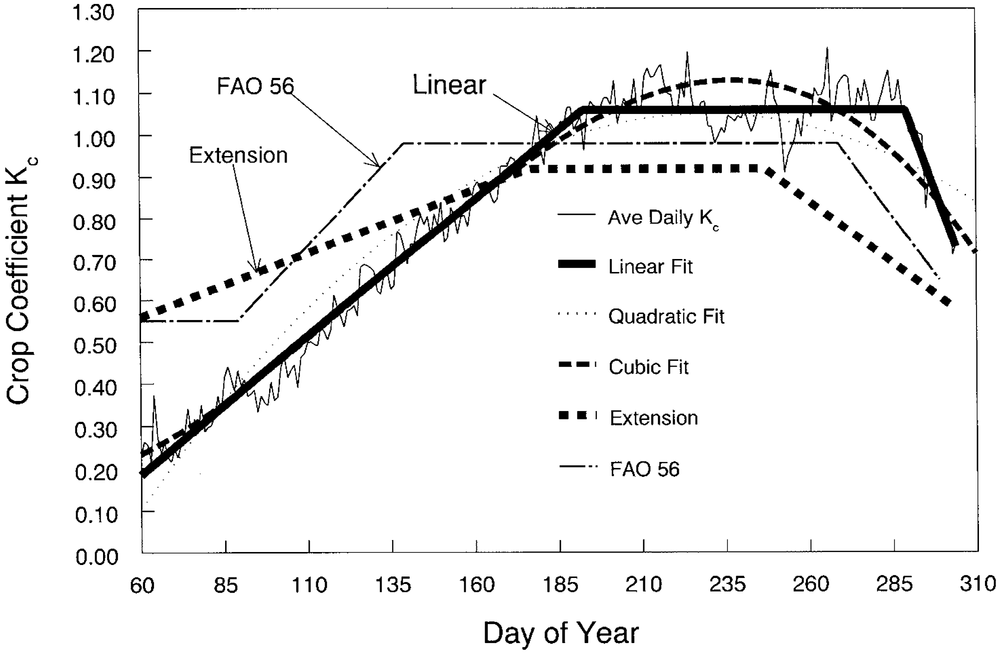


Fig. 4 Average daily crop coefficient with linear, cubic, and quadratic regressions and Cooperative extension bulletin K_c curve and curve calculated using FAO 56 (Allen et al. 1998)

4.5 m. This resulted in the mid-season value increasing to 0.98.

The individual crop coefficient equations for each method are:

linear fit to lysimeter data

$$\begin{aligned} K_c &= -0.2121 * \mathrm{DOY} + 0.006606 * \mathrm{DOY} \text{ for DOY } 60-192 \\ K_c &= 1.06 \text{ for DOY } 193-289 \\ K_c &= 7.448 - 0.0221 * \mathrm{DOY} \text{ for DOY } 290-304 \end{aligned} \tag{1}$$

extension bulletin linear fit

$$\begin{aligned} K_c &= 0.55 + 0.0031 * (\mathrm{DOY} - 57) \text{ for DOY 57 to 176} \\ K_c &= 0.92 \text{ for DOY 177 to 247} \\ K_c &= 0.92 - 0.006(\mathrm{DOY} - 247) \text{ for DOY 248 to 314} \end{aligned} \tag{2}$$

FAO 56 method

$$\begin{aligned} K_{c\,\mathrm{ini}} &= 0.55 \text{ for DOY } 60-90 \\ K_{c\,\mathrm{mid}} &= 0.98 \text{ for DOY } 140-270 \\ K_{c\,\mathrm{end}} &= 0.65 \text{ for DOY } 300 \end{aligned} \tag{3}$$

quadratic fit to lysimeter data

$$K_c = 0.9758 + 0.2223 * D - 0.1646 * D^{\wedge 2} \tag{4}$$

cubic fit to lysimeter data

$$K_c = 0.9695 + 0.3691 * D - 0.1549 * D^{\wedge 2} - 0.07034 * D^{\wedge 3} \tag{5}$$

where DOY is day of the year and $D = (\mathrm{DOY} - 182)/70.76$, where D is a fitting parameter.

Statistical analysis of the cubic expression determined that the cubic term was significant ($P = 0.0013$), indicating that going from a quadratic to cubic equation improved the fit to the data.

Inspection of Fig. 4 shows that the cubic and linear equations fit the data on the developing portion of the curve very well. The quadratic expression overestimates the values in this section of the curve. None of the curves fit the mid-season data very well, but the linear expression is probably the best, on average, of the three regression equations. The lack of fit is due to the dip in ET_c which occurs in August following harvest (DOY 240). The end portion of the graph is best represented by the linear fit. Any of the equations could be programmed into a computerized scheduling program using only the day of the year as the required input for calculating the crop coefficient. These data are representative of the conditions in the San Joaquin Valley of California for drip or fanjet irrigation on a 1–3 day watering interval.

The three-segment linear model was used to calculate the monthly water use from 1991 to 1994 for comparison with the data measured by the lysimeter for this period. The resulting data are given Table 1 along with the measured data. The calculated annual total ET_c ranged from10% less to 10% greater than the measured values. This is reasonably good agreement and would be acceptable for irrigation scheduling purposes. Additionally, each of the crop coefficients was used to calculate crop water use with the 1990 weather data set. The calculated crop water use is given in Table 2 for each of the equations.

The seasonal water requirement was approximately the same regardless of the crop coefficient selected. When evaluating the utility of the crop coefficient for irrigation scheduling, the important consideration is the temporal distribution of the applied water. The K_c

Table 2 Crop water use (mm) calculated using all crop coefficients and 1990 weather data

Linear fit to lysimeter data	Quadratic fit to lysimeter data	Cubic fit to lysimeter data	Extension bulletin	FAO 56
1023	1029	1031	1003	1076

graphs in Fig. 4 show that using the extension bulletin coefficient, the quadratic coefficient, or the FAO curve will result in overirrigation early in the season and underirrigation later in the season. Early season overirrigation is not desirable because it will not allow the crop to use soil water stored in winter, thus resulting in no soil water storage capacity for any overirrigation late in the season. Also, overirrigation early in the growing season may result in excessive deep percolation and transport of nutrients and other agricultural chemicals to the groundwater. The maximum value for K_c based on the linear equation from the lysimeter study is larger than the generalized values reported in the extension bulletin for clean-soil-surface stone fruit orchards (Snyder et al. 1989) and the mid-season value of the FAO crop coefficient adjusted for bare soil.

From a practical perspective, irrigation scheduling of peach trees based on regional weather station-generated ET_o and a simple canopy light interception model would be desirable and usually adequate. Mid-day canopy light interception was one parameter that correlated well with K_c and that was able to account for the greatest amount of variability in the K_c values (Fig. 5) according the following equation:

$$K_c = 0.082 + 1.59 * (\text{Proportion midday light interception}),\quad R^2 = 0.86 \qquad (6)$$

Equation 6 accounted well for the year-to-year variability (1990 had lower K_c and correspondingly lower light interception values than the other four years) and the seasonal variability (increasing K_c values correlated well with increasing light interception). Overall, 86% of the total variability was accounted for by this one factor. Attempts to account for the remaining 14% of the variability, which was mainly due to day-to-day and week-to-week variations, were largely unsuccessful. Using multiple regression, factors such as maximum air temperature (+), vapor pressure deficit (+), wind speed (−) and solar radiation (−) were statistically significant but only accounted for an additional 1–2% of the variability, and thus are of questionable practical usefulness. It is possible that some random variability associated with the ET_o calculations, weather station microclimate (which may be different from the orchard microclimate), and accuracy of the weather station instruments could account for the remaining 14% variability. Also, based on energy balance theory, the effect of individual environmental factors on tree K_c values would not be expected to be linear or independent of other factors (Annandale and Stockle 1994). Therefore, multiple regression would probably not be a very effective tool for quantifying the significance of these environmental factors.

Several sources of data suggest the relationship between crop coefficients and canopy light interception obtained in this experiment might be fairly universal for different species and tree ages. For example, a similar weighing lysimeter at the Kearney Agricultural Center, but planted to grapes, generated an almost identical relationship (L.E. Williams, unpublished data). Also, Fereres et al. (1982) used percent shaded area under the tree (which is essentially the same as percent light interception by the canopy) to predict young almond tree water use as a proportion of mature tree K_c. Using a peak K_c of 0.92 from their earlier studies (Snyder et al. 1989), this relationship is again almost identical to the one we obtained with the peach lysimeter.

The differences in the seasonal peach tree K_c pattern from this experiment and the pattern published for deciduous fruit trees (Snyder et al. 1989) may be due to canopy light interception. The published K_c values were developed using mainly almond as the tree species. Almond has a spur-type growth habit and therefore develops a canopy much more quickly than peach trees in the spring. This may be why it initially has greater K_c

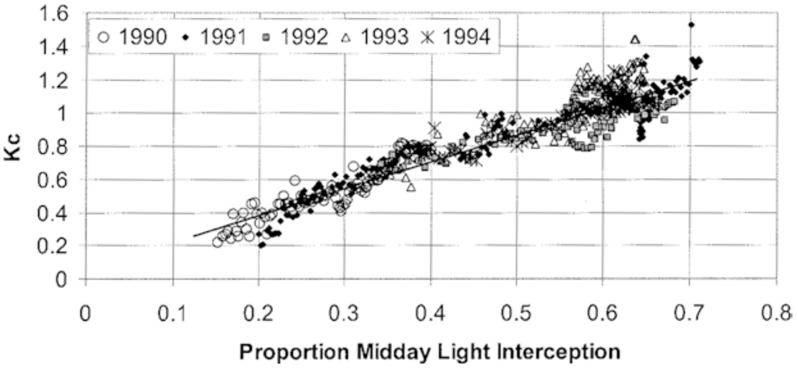


Fig. 5 Mature peach tree crop coefficients (K_c) as a function of the proportion of available light intercepted by the canopy at mid-day. Equation of the regression line is $y = 1.59x + 0.082$, $R^2 = 0.86$

Table 3 Yield data from lysimeter and control treatment

	Lysimeter trees				Field trees (control treatment)			
	Yield		Fruit load	Fruit weight	Yield		Fruit load	Fruit weight
	(kg/tree)	(t/ha)	(no./tree)	(g/fruit)	(kg/tree)	(t/ha)	(no./tree)	(g/fruit)
1990	28.3	31.7	137	207.3	26.7	29.9	123	216.7
1991	51.3	57.5	182	281.7	45.3	50.8	164	275.3
1992	63.7	71.4	334	190.8	58.0	65.0	293	197.6
1993	66.7	74.8	334	199.7	54.6	61.2	258	211.9
1994	45.2	50.7	229	197.6	29.3	32.8	136	215.6

values than peach trees. Once the spur canopy is developed, almond trees do not tend to produce much vigorous shoot growth, while peach trees continue to grow vigorously into the summer. Therefore, by mid-season, one might expect peach trees of a given size to have greater light interception than almond trees of the same dimension. Again, the K_c values reflect these expected differences. The experiments discussed here were all conducted within the same climatic zone of California. It would be valuable to test this relationship in other climatic zones to see whether it can be universally applied.

Evapotranspiration includes both tree transpiration and soil evaporation. The amount of soil evaporation depends on the type and frequency of irrigation especially for young trees or in early spring when canopy light interception is low. For our experiment, irrigation events occurred frequently but only wet about 20–25% of the soil area assigned to the tree. On the days the lysimeter was covered with plastic, it was presumed the lysimeter was measuring only tree transpiration. The regression of K_c vs canopy light interception on these dates produced the following equation

$$K_c = 0.007 + 1.48 * (\text{Proportion midday light interception}),\quad R^2 = 0.93 \tag{7}$$

Comparing this equation with Eq. 6 suggests that soil evaporation accounts for 24% of ET_c at 20% canopy cover but only 13% of ET_c when the canopy is intercepting 70% of available light. With different irrigation systems and frequencies, these values would be expected to change. To evaluate the extent of these changes it would be useful to model the transpiration and evaporation components of ET separately. Tree transpiration would primarily be a function of canopy light interception and soil evaporation a function of soil, irrigation, and meteorological parameters. Although complex soil evaporation models have been developed, rather simple models requiring a minimum of inputs have shown good results (Ben-Asher et al. 1983; Reddy 1983; Katul and Parlange 1992; Ritchie and Johnson 1990). Therefore, it should be feasible to develop soil evaporation under partial canopy cover for field crops (Black et al. 1970; Tanner and Jury 1976; Lascano et al. 1987) and forest trees (Wallace et al. 1999) but not, to our knowledge, for orchards.

The yield data from the lysimeter trees and the control treatment from the replicated trial are given in Table 3. The data show that there was a slightly higher yield on the lysimeter trees than on the control. This was mainly due to more precise care given the lysimeter trees. Pruning, hand thinning, and other cultural practices were more carefully performed. The fruit size was smaller on the lysimeter than in the field but the numbers were higher, resulting in the higher yield. The higher fruit numbers on the lysimeter were responsible for the smaller size. It should be noted that the yields were excellent for both the lysimeter and field trees.

Conclusions

A large weighing lysimeter was used in a 4-year study in the San Joaquin Valley of California to determine the crop water requirement and a crop coefficient for a late-maturing peach cultivar (O'Henry). The average water use for the four years of the study was 1,034 mm per year. This is comparable to the average water use in commercial production. The crop coefficient was calculated as the ratio of the measured crop water use and the potential evapotranspiration determined using the CIMIS Penman equation. The K_c data were plotted against the day of the year (DOY) and segmented linear, quadratic, and cubic regressions were used to characterize the data. The K_c data were compared to the University of California K_c recommendations and a crop coefficient curve based on the FAO 56 procedure. A three-segment linear and the cubic regression had the best fit to the data. The maximum K_c value determined in this experiment for the level section of the linear fit was 1.06. The recommended maximum value for use with deciduous fruit trees in California is 0.92 and the FAO curve had a maximum K_c value of 0.98. Either the three-segment linear equation determined in this research or the cubic equation are suitable for use in irrigation scheduling of late-season peaches using surface drip or fanjet irrigation under conditions similar to the San Joaquin Valley. Additional studies evaluated the relationship between the crop coefficient and the mid-day canopy light interception. The analysis determined that there was a good correlation between the mid-day light interception and the crop coefficient. This relationship was also adequate for irrigation scheduling.

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