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Water use of young Thompson Seedless grapevines in California

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Abstract Water use of Thompson Seedless grapevines during the first 3 years of vineyard establishment was measured with a large weighing lysimeter near Fresno, California. Two grapevines were planted in a 2×4×2 m deep lysimeter in 1987. The row and vine spacings in the 1.4-ha vineyard surrounding the lysimeter were approximately 3.51 and 2.15 m, respectively. Vines in the lysimeter were furrow-irrigated from planting until the first week of September in 1987. They were subsequently irrigated with subsurface drip-irrigation whenever they had used 2 mm of water, based upon the area of the lysimeter (equivalent to 8 liters per vine). The trellis system, installed the second year, consisted of a 2.13 m long stake, driven 0.45 m into the soil with a 0.6 m cross-arm placed at the top of the stake. Crop coefficients (K_c) were calculated using measured water losses from the lysimeter (ET_c) and reference crop evapotranspiration (ET_o) obtained from a CIMIS weather station located 2 km from the vineyard. Water use of the vines in 1987 from planting until September was approximately 300 mm, based on the area allotted per vine in the vineyard surrounding the lysimeter. Daily water use just subsequent to a furrow-irrigation event exceeded ET_o (>6.8 mm day^{-1}). Water use from budbreak until the end of October in 1988 and 1989 was 406 and 584 mm, respectively. The initiation of subsurface drip-irrigation on 23 May 1988 and 29 April 1989 doubled ET_c measured prior to those dates. Estimates of a 'basal' K_c increased from 0.1 to 0.4 in 1987. The seasonal K_c in 1988 increased throughout the season and reached its peak (0.73) in October. The highest K_c value in 1989 occurred in July. It is suggested that the seasonal and year-to-year variation in the K_c was a result of the growth habit of the vines due to training during vineyard establishment. The results provide estimates of ET_c and K_c for use in scheduling irrigations during vineyard establishment in the San Joaquin Valley of California and elsewhere with similar environmental conditions.

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Introduction

There have been numerous estimates of crop water use for mature grapevines. However, estimates of crop water use for grapevines during the first 3 years of vineyard establishment are limited (Myburgh et al. 1996; Peacock et al. 1977). Evapotranspiration techniques that have been used previously for grapevines required assessments of various soil and/or water parameters (Araujo et al. 1995a; Erie et al. 1982; Grimes and Williams 1990; Stevens and Harvey 1996; van Rooyen et al. 1980) that may limit their accuracy. Sap flow sensors have been used on young and mature vines in conjunction with models of soil water evaporation to estimate crop evapotranspiration (ET_c) (Lascano et al. 1992; Ginestar et al. 1998; Yunusa et al. 1997a, 1997b). The reliability of sap flow sensors, especially on large vines, has been questioned (Tarara and Ferguson 2001). Micrometeorological methods to estimate sensible and latent heat flux in vineyards also have been used (Oliver and Sene 1992; Spano et al. 2000; Yunusa et al. 2000). Such techniques require large areas of uniform fetch and extensive instrumentation (Grimmond et al. 1992). Unfortunately, individual vineyard blocks in many grape production areas are quite small, limiting the use of micrometeorological methods under those conditions.

Lysimeters are the standard for ET_c measurements (Prueger et al. 1997). Drainage lysimeters have been used to measure the water use of grapevines (Evans et al. 1993; Rollin et al. 1981; van Rooyen et al. 1980). Such lysimeters can provide accurate crop water-use values on a weekly basis (Buwalda and Lenz 1995) and daily estimates when used in conjunction with extensive measurements of the soil water content within the lysimeter (Evans et al. 1993). However, greater accuracy and sensitivity can be obtained with weighing lysimeters, which measure ET directly (Hatfield 1990). With the appropriate instrumentation, weighing lysimeters can accurately determine ET_c on an hourly or shorter time basis.

A large weighing lysimeter was constructed near Fresno, California, to measure the ET of Thompson Seedless grapevines (Phene et al. 1991). Water use during the first season was recorded by manually reading the scale on a near-daily basis. Continuous hourly measurements of vine ET were determined during the second and third years of the study. Vine ET was then used to develop crop coefficients for use in irrigation management of vines used for raisin and table grape production in the San Joaquin Valley of California. Results presented here describe the water use of grapevines during the first 3 years of vineyard establishment.

Materials and methods

A 2×4×2 m deep weighing lysimeter was installed at the University of California Kearney Agricultural Center located in the San Joaquin Valley of California (36°48′ N, 119°30′ W) in 1986. Two *Vitis vinifera* L. (cv. 'Thompson Seedless', clone 2A) grapevine cuttings were planted in the lysimeter on 9 April 1987. The two vines were 2.15 m apart and 0.925 m from either end of the 4 m long lysimeter. The vines were 1.0 m from the sides of the lysimeter. Cuttings were also planted in the vineyard surrounding the lysimeter with vine and row spacings of 2.15 and 3.51 m, respectively (7.55 m^2 per vine). Row direction was east–west. The vines planted on either side of the lysimeter down the row were 2.15 m from the respective east or west vine inside the lysimeter. The vineyard was approximately 1.4 ha (168×82 m) and was surrounded by a mixture of annual and perennial crops.

Vines within the lysimeter were furrow-irrigated from planting until the first week in September 1987, after which they were subsurface drip-irrigated. Two furrows were dug manually, one on either side of the cuttings, within the lysimeter. The edge of the furrows was located 0.15 m from the cuttings. Furrows were approximately 0.4 m wide at the top, 0.2 m wide at the bottom, 0.3 m in depth, and 3.8 m in length (almost the entire length of the lysimeter, 4.0 m). Vines in the surrounding vineyard were furrow-irrigated all season long. Vine water use was determined by reading the scale manually almost on a daily basis. Therefore, readings were taken just prior and subsequent to a furrow-irrigation to determine the amount of water to apply. The vines were allowed to grow without any support the first year. During the winter, each vine was pruned to one, two-bud, spur.

Drip-irrigation for the remainder of the vineyard, and the trellis system, were installed during vine dormancy of the first growing season (January 1988). The trellis of the vines within the lysimeter consisted of a 2.13 m long wooden stake driven 0.45 m into the soil at each vine. A 0.6 m cross-arm was placed atop the stake and wires attached at either end of the cross-arm to support the vine's fruiting canes. Wooden end posts, 16 cm in diameter, with cross-arms, were placed in the soil at both ends of the lysimeter for additional support. The trellis for the vines in the lysimeter was self-contained and not attached to the trellis system used down the remaining sections of the row to ensure that it was part of the lysimeter mass.

During the second growing season, a single shoot from each vine was trained up the stake in order to form the trunk. Any clusters that were present at this time were removed. Once the shoot's apex was 15 cm above the cross-arm, it was topped to stimulate lateral shoot growth and to form the head of the vine. Midway through the growing season all remaining lateral shoots that had formed along the future trunk were removed. During vine dormancy, the vines were pruned to two, 12-node, fruiting canes (these canes contained the forthcoming growing season's cluster primordia). The third growing season (1989) was the first cropping year. Standard horticultural practices to control disease and insect pests of grapevines were performed as necessary by field station personnel each year.

The soil container of the lysimeter was weighed with a balance beam and load cell configuration, with most of the weight being eliminated using counterweights. The soil, a Hanford fine sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent), 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 filled manually in 0.15-m layers and compacted to approximately the original bulk density (1.57 Mg/m^3). Before filling, stainless steel fritted tubing placed at a 0.6 m spacing was installed in a 2.4 mm-thick layer of diatomaceous earth at the bottom of the lysimeter to act as a drain. The calibrated accuracy of the lysimeter was ± 0.025 mm of water and the overall resolution of the system was 400 g or 0.05 mm of water. The hourly loss of mass by the lysimeter was assumed to be due to the water loss by transpiration, soil evaporation and drainage. A more detailed description of the lysimeter and its construction can be found in Phene et al. (1991).

Vines in the lysimeter after 5 September 1987 and the rest of the vineyard at the beginning the 1988 growing season were irrigated at a rate of 4 l h^{-1} with in-line drip emitters, spaced every 0.30 m. The drip tubing within the lysimeter was buried approximately 0.4 m below the surface of the soil, 0.3 m from the vines. Half of the vines within the surrounding vineyard were irrigated with subsurface drip-irrigation and the other half with the drip tubing attached to a wire suspended in the row 0.4 m above the soil surface. Irrigation water for the lysimeter was supplied from two 300-l water tanks suspended on the weighbridge supporting the lysimeter (to insure that this water was a part of the lysimeter's mass). The lysimeter's mass was recorded hourly to determine ET_c of the two vines and the lysimeter soil surface, and the change in mass was compared with a 16-l threshold value of water loss, equivalent to 2 mm ET_c over the 8 m^2 lysimeter surface. 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 a baseline for the next day. No drainage was recorded during the 3-year study period. A datalogger (21X Micrologger, Campbell Scientific) was used to monitor and control the system and to communicate with a computer at the Water Management Research Laboratory (WMRL) in Fresno, California. Data were downloaded to the WMRL computer for processing daily at midnight. The number of irrigations per day, throughout the 1988 and 1989 growing seasons, ranged from 0 to 4.

Reference crop evapotranspiration (ET_o) data were obtained from a California irrigation management information system (CIMIS) weather station located 2 km from the vineyard site. Variables measured and calculations used to determine hourly and daily ET_o from CIMIS can be found in Snyder and Pruitt (1992). The summation of hourly ET_o values was used with the summed hourly values of measured vine evapotranspiration (ET_c) to calculate the daily crop coefficient. The crop coefficient (K_c) was calculated as the ratio of ET_c/ET_o. The ET_c measured by the lysimeter was adjusted to an area equivalent loss of an individual vine in the lysimeter

(4 m^2 of surface area) to that of an individual vine in the surrounding vineyard (7.55 m^2 of surface area) by multiplying by 0.53. It was assumed that soil water evaporation in the area outside the lysimeter, not measured, especially after the initiation of drip-irrigation in 1988 and 1989, was minimal in the absence of rainfall.

Soil water content (SWC) within the lysimeter was monitored using the neutron back-scattering technique with a neutron moisture probe (Model 503 DR Hydroprobe moisture gauge; Boart Longyear, Martinez, Calif.). Two access tubes were placed approximately 0.5 m from each vine within the row (approximately 1.0 m between the two tubes) and inserted to a depth of 1.8 m. Readings were taken at depths of 0.23, 0.45, 0.75, 1.05, 1.35, and 1.65 m from the soil surface. The neutron probe was calibrated according to Dickey and Schwankl (1980) and water content values expressed as percent by volume (θ_v). Field capacity of this soil type was approximately 22.0 θ_v while SWC at a soil moisture tension of −1.5 MPa was approximately 8.0 θ_v (Araujo et al. 1995a).

Leaf area of vines within the lysimeter was estimated using non-destructive methods. At various times during the growing season (see Results section for specific dates) the number of shoots and individual shoot lengths of each vine within the lysimeter were measured. At the same time a minimum of 20 individual shoots of varying lengths were collected from vines in the surrounding vineyard. The length of each shoot was measured and leaf area determined with an area meter (model LI-3100; Li-Cor, Lincoln, Neb,). The relationship between shoot length and leaf area was determined via regression analysis on each date that data were collected. In most cases a linear or quadratic equation was used to fit the data with R^2 values in excess of 0.9. Total leaf area of vines in the lysimeter was then calculated based upon the relationship between shoot length and leaf area and the number of shoots per vine. Once the measurement of shoots on the lysimeter-grown vines became too demanding in 1989, the leaf areas of vines ($n = 3$) in the vineyard surrounding the lysimeter were destructively determined and the values assumed to be representative of the lysimeter vines. There were no obvious visual differences in canopy size between the two vines growing in the lysimeter and vines growing elsewhere in the vineyard. Estimated leaf area of vines in the lysimeter compared favorably with leaf area measured on vines growing in the surrounding vineyard during 1989.

Degree-day data were obtained from the University of California Statewide Integrated Pest Management Project's website. Temperature data used in calculating degree-days were obtained from the CIMIS number 39 weather station at the Kearney Agricultural Center. Degree-days were calculated using the sine method with a lower threshold of 10°C.

Results

Amounts of rainfall occurring during the three growing seasons were 12 mm in 1987, 62 mm in 1988 and 46 mm in 1989 (Table 1). Almost half of the rainfall in 1989 occurred on 20 September. Reference crop evaporation (ET_o) from the planting date in 1987 to the beginning of drip irrigation was 887 mm, while that to 7 October was 1,052 mm. Reference crop ET for the 1988 and 1989 growing seasons, from budbreak until the last day in October, was 1,147 and 1,182 mm, respectively. Over the same time period, accumulated degree-days (DDs) were 2,664 in 1988 and 2,537 in 1989.

Furrow irrigations in 1987 took place on six dates, between the day after planting and the end of August (Table 2). The amount of water used from one furrow-irrigation event to another was generally less than that applied. Daily ET_c values were greatly affected by an irrigation event (Fig. 1). Although ET_c was not determined on every date subsequent to an irrigation event, the amount of water depleted from the lysimeter on those dates that were measured was considerable. For example, when water was applied on 28 May (DOY 148), ET_c for the next 3 days (28–31 May) was equivalent to 6.8 mm per day. However, by 2 June (DOY 153), ET_c had dropped to 3.8 mm per day. On 6 August, vines were irrigated at 1100 hours and the mass of the lysimeter recorded at 1200 hours. Between 1200 hours on 6 August and 1300 hours on 7 August the loss of water was equivalent to 6.9 mm. Water loss between 7 August and 10 August amounted to 3.7 mm per day. Thus, furrow-irrigation resulted in a wet soil surface that caused a large soil surface evaporation component following an irrigation event.

Due to technical difficulties, reliable measurements of vine water use once drip-irrigation commenced in 1987 occurred only on a few days. Each of the last two data points in Fig. 1 represent water use measured on two consecutive days.

High soil-water evaporation following a furrow-irrigation event greatly elevated K_c values. The K_c on days following an irrigation event occasionally exceeded unity, but then rapidly declined. With the development of leaf area as the season progressed, the crop coefficient on the days preceding irrigation gradually increased,

Table 1 Rainfall events recorded in 1987 between planting and 10 October and during the 1988 and 1989 growing seasons between budbreak and 31 October. Date of budbreak in 1988 was 11 March and in 1989 it was 20 March

Year	Calendar date	Day of year	Rainfall (mm)
1987	1 May	120	3.0
	15 May	135	8.9
1988	14 April	105	27.6
	19 April	110	26.5
	20 April	111	0.8
	21 April	112	1.7
	22 April	113	4.5
	23 April	114	1.1
1989	22 March	81	3.3
	29 March	88	8.9
	5 May	125	11.9
	12 May	132	1.8
	20 September	263	20.0

Table 2 Dates and amount of applied water for furrow-irrigation in 1987 and measured water use (ET_c) between dates of application. Values are based on an area of 7.55 m^2 per vine. Values in parentheses in the Date of irrigation column represent day of year (DOY)

Date of irrigation	Irrigation amounts (mm)	Inclusive dates of ET_c	ET_c (mm)
10 April (100)	37.1	10 April to 4 May	32.5
5 May (125)	58.1	5 May to 27 May	50.1
28 May (148)	63.2	28 May to 23 June	60.5
24 June (175)	61.2	24 June to 16 July	51.0
17 July (198)	52.6	17 July to 5 August	48.5
6 August (218)	58.8	6 August to 4 September	46.8

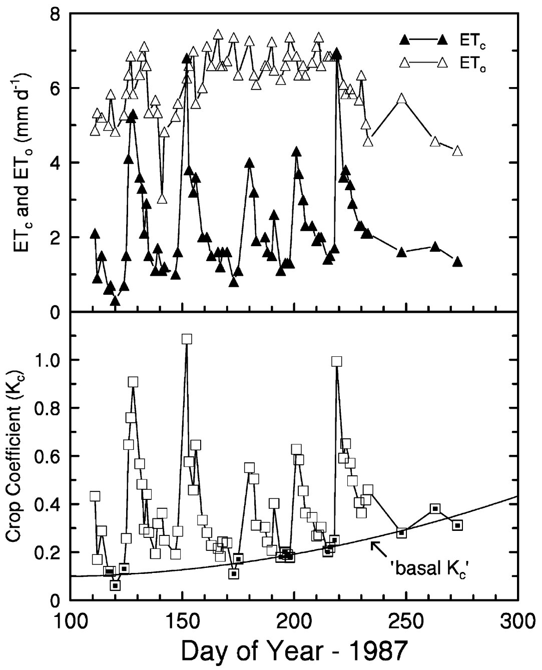

Fig. 1 Thompson Seedless measured water use (*ET_c*), reference crop ET (*ET_o*) and the calculated crop coefficient (K_c) during the first year of vine growth. The vines were planted on 9 April. Water use was measured with a weighing lysimeter and expressed on an area per vine basis of 7.55 m^2. The regression line using the lowest K_c values ($y = 0.155 - 0.001304x + 0.00000744x^2$) where x equals DOY, represents a 'basal' crop coefficient. The *filled data points* were used to determine the 'basal' K_c

indicating increasing vine transpiration. Estimated leaf area per vine on 10 July (DOY 161) and 22 September (DOY 265) were 0.75 and 1.4 m^2, respectively. A polynomial regression line was calculated through the lowest K_c points and expressed on a DOY basis. The resulting daily 'basal' K_c was multiplied by daily ET_o to estimate vine transpiration from planting through 4 September and 10 October (Table 3). The estimated vine transpiration of 140 mm was approximately 50% of the measured total vine water use between planting and the beginning of drip-irrigation, implying that soil evaporation was approximately 50% of the first-year water use with furrow-irrigation.

Table 3 Amount of irrigation, measured wateruse (ET_c) and reference crop evapotranspiration(ET_o) and estimated vine transpiration from date of planting (9 April) until 4 September, 1987. Estimated vine transpiration was calculated using the 'basal' crop coefficients shown in Fig. 1. Daily values of ET_o and 'basal' crop coefficients were multiplied and then summed from planting until the specified date. Values are based upon the area per vine within the vineyard surrounding the lysimeter (7.55 m^2)

Dates	Amount of irrigation	Measured ET_c	ET_o	Estimated vine transpiration
	(mm)			
9 April to 4 September	331	289	887	140
9 April to 10 October	–	–	1,052	199

The second growing season during vineyard establishment is when the trunk and head of a grapevine are formed. Early on, only one shoot per vine is allowed to grow and it is trained to grow up the stake to form the trunk. It is not until lateral shoot growth takes place along the primary shoot (future trunk) that significant leaf area is formed. The shoot forming the trunk reached the cross-arm the last week in May and was topped 2 weeks later (leaf area was estimated to be approximately 1.5 m^2 per vine). At this time lateral shoots grew vigorously from the top eight nodes. Lateral shoots from below the top eight nodes had already been removed.

The high ET_c values early in the 1988 season (DOY 110–140) (Fig. 2) was due to evaporation from the wet soil surface following the large amount of rainfall that occurred during the second and third weeks of April (Table 1). During the period from 12 April (DOY 103) to 9 May (DOY 130) cumulative ET_c was 39.4 mm, which was equivalent to 63% of the rain that fell during April. A large increase in ET_c occurred when daily irrigations commenced on DOY 144 (Fig. 3). ET_c increased from 0.5 mm on DOY 143 to 1.62 mm on DOY 144, when 2.75 mm of water was applied and the K_c

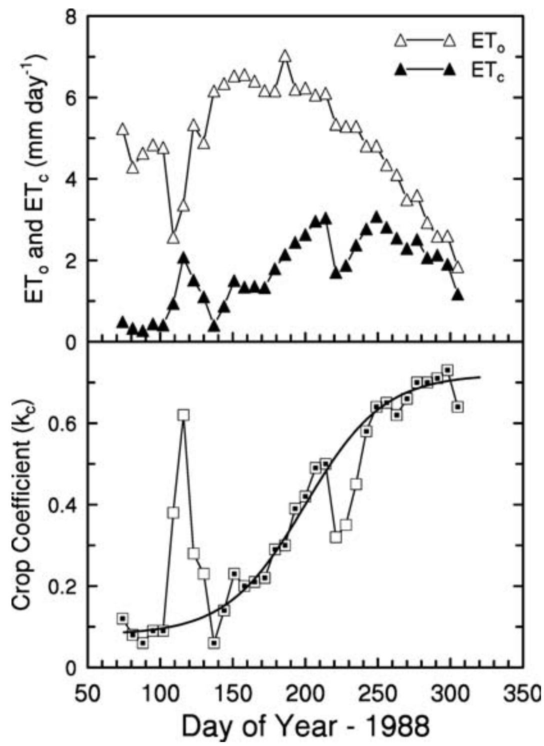

Fig. 2 Daily (weekly amounts/7) vine water use (*ET_c*), reference crop evapotranspiration (*ET_o*) as a weekly average, and the resulting K_c measured during the second year of vine establishment. Date of budbreak was 11 March. Vines were trained up the trellis stake in order to form the trunk and ultimately the head of the vine during the second year. The K_c curve was the following: $y = 0.08 + (0.64/(1 + e^{(-(x - 200)/27)}))$, where x equals DOY. The *filled data points* were used to generate the equation

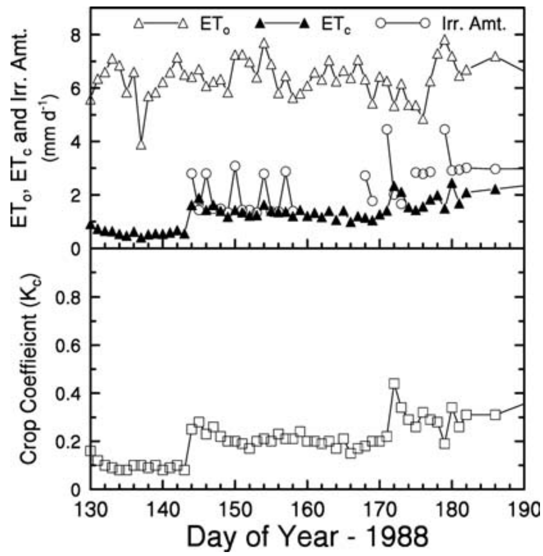

Fig. 3 Daily vine water use (ET_c), reference crop evapotranspiration (ET_o) and crop coefficient (K_c) measured from DOYs 130–190 of the 1988 growing season. Irrigation amounts (*Irr. Amt.*) are also given and are expressed on an area per vine basis of 7.55 m^2. Irrigation began on DOY 144. There were several days in which the vines were not irrigated

increased from 0.08 to 0.24 over the same time-frame. Water use remained fairly constant for the next 27 days despite varying amounts of applied water and no applied water during the period DOY 159–168. Applied water amounts of greater than 4 mm per day on DOYs 171 and 179, did increase ET_c and the K_c on DOYs 172 and 180, respectively. After the end of June (DOY 183), irrigations within the lysimeter replaced ET_c whenever 16 l of water was lost from the lysimeter. Water use increased from that point on until DOY 210 (Fig. 2). On that date, three or four lateral shoots were removed from the upper portion of the newly formed trunk on each vine within the lysimeter. The removal of these shoots comprised approximately 50% (4 m^2) of the total estimated leaf area (8 m^2) per vine at that time. Water use and the K_c increased rapidly thereafter due to vigorous growth of the remaining four lateral shoots (two of which were retained as next year's fruiting canes at pruning) growing from the head of each vine. The K_c remained quite high right up until the end of October (DOY 304). Unfortunately, no estimation of leaf area at the end of the season was made that year. It should be pointed out that lateral shoots arising out of the four lateral shoots left on the vine grew quite vigorously and some extended nearly midway between the rows.

The first measurement of soil water content (SWC) took place just prior to the first irrigation in 1988 (Fig. 4). On the second measurement date the use of subsurface drip-irrigation is reflected by the increase in SWC at the 0.45 and 0.75 m depths, but SWC at the 0.23 m depth declined. The decrease in SWC at the 0.45 and 0.75 m depths on the third date was due to a lack of irrigation between DOYs 159 and 168. The application of more than 4 mm per day on DOYs 171 and 179

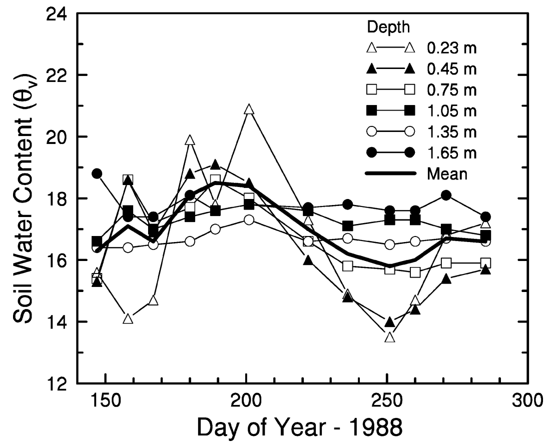

Fig. 4 Soil water content (*SWC*: expressed as percent by volume = θ_v) measured in the lysimeter throughout the 1988 growing season. Each data point is the mean of measurements taken in two access tubes. The mean is of all depths in both access tubes. Soil water content at field capacity was approximately 22.0 θ_v while that at a soil moisture tension of −1.5 MPa was approximately 8.0 θ_v

resulted in an increase in SWC at the 0.23 m depth and the wetting of the soil surface. Soil water content at a depth of 1 m or more was relatively constant throughout the growing season.

The third growing season began with the vines having two fruiting canes left after pruning. Leaf area per vine estimated shortly after irrigations commenced was approximately 5 m^2 (Table 4). Maximum leaf area was approximately 13 m^2 per vine in September.

Drip-irrigation within the lysimeter commenced on 29 April (DOY 119) in 1989. ET_c increased from 1.31 mm per day in the week prior to the first irrigation to 3.38 mm per day in the first week of irrigation (Fig. 5). The crop coefficient increased from 0.29 to 0.64 during the same time-frame. The dip in ET_c and ET_o during the week of 9 May (DOY 129) was due to two rainfall events (Table 1). Irrigation was resumed for the next 3 weeks at amounts comparable to ET_c except for the week of 29 May (DOYs 149–155) when the vines received no applied water. Subsequent to that period ET_c and the K_c increased rapidly, both reaching a peak in the week of 12 July (DOYs

Table 4 Estimated leaf area per vine during the 1989 growing season. Date of budbreak was 20 March (DOY 79). Degree-day data were obtained from the UC Statewide Integrated Pest Management Project using temperature data from the CIMIS number 39 weather station (at the Kearney Agricultural Center). A lower threshold of 10°C was used

Calendar date	Day of year	Degree-days from 50% budbreak	Leaf area (m^2 $vine^{-1}$)
25 April	115	296	4.5
23 May	143	554	5.9
7 June	158	706	7.4
11 July	192	1176	9.4
9 August	221	1627	11.9
13 September	256	2093	12.9

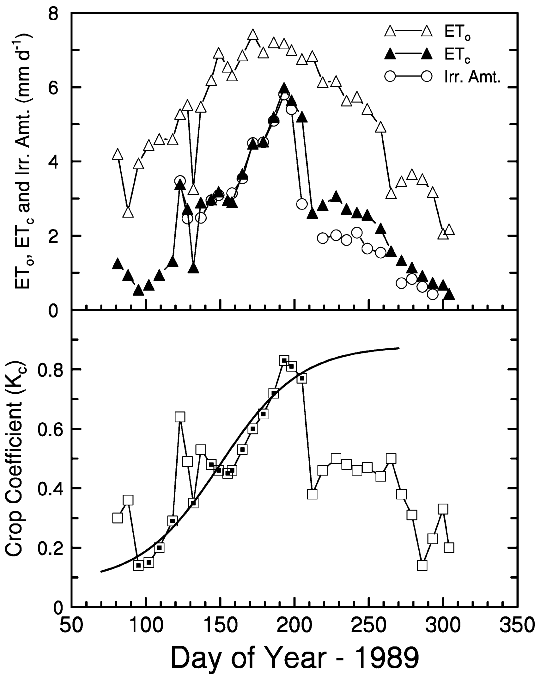

Fig. 5 Daily vine water use (*ET*$_c$), reference crop evapotranspiration (*ET*$_o$), irrigation amount (*Irr. Amt.*) and crop coefficient (K_c) measured during the 1989 growing season. Date of budbreak was 20 March. There are several intervals in which the vines received no applied water. The crop coefficient as a function of DOY was the following: $y = 0.08 + (0.8/(1 + e^{(-(x - 150)/27)}))$, where x equals DOY. Other information is as given in Fig. 2

194–200). From DOY 206 onwards, the lysimeter experienced both electrical and mechanical problems. During the week of 19 July (DOYs 199–206) vines were only irrigated with approximately 50% of the amount of water that they used. The following week they were not irrigated and ET_c decreased from 5.2 mm per day to 2.6 mm per day. At this time a marked decline in the K_c occurred. By DOY 220, however, ET_o values declined in roughly the same proportion as ET_c and the K_c was constant until DOY 270.

The SWC started high in the 1989 growing season (Fig. 6) and decreased at all depths even after irrigation started and a 9 May (DOY 129) rainfall event. The resumption of irrigation the following week increased SWC, with a drop during the week there were no irrigations (DOY 166), the exception being SWC at the 0.23 m depth, which increased. Soil water content decreased from DOY 189 until DOY 222 due to a combination of deficit irrigation and no irrigation for 1 week. Once irrigation resumed, at amounts less than ET_c, SWC leveled off and remained relatively constant until the last measurement date.

Discussion

Vine water use (ET_c) from planting in 1987 until the beginning of drip-irrigation on 5 September was equivalent to 289 mm, while ET_c from budbreak until the end of October in 1988 and 1989 was 406 and 584 mm, respectively. These values are similar to the highest ET_c values reported by Myburgh et al. (1996) but greater than those reported by Peacock et al. (1977) for water use during the first 3 years of vineyard development. The differences between our results and those of Peacock et al. (1977) may have been due to the fact that the vines in this study were flood-irrigated during the first year, and in years 2 and 3 drip-irrigation was supplied whenever 16 l of water was lost from the lysimeter. The vines in the Peacock et al. (1977) study were either drip- or sprinkler-irrigated (two different treatments) all 3 years and water application amounts were those required to maintain soil moisture tension at between −0.005 and −0.015 MPa.

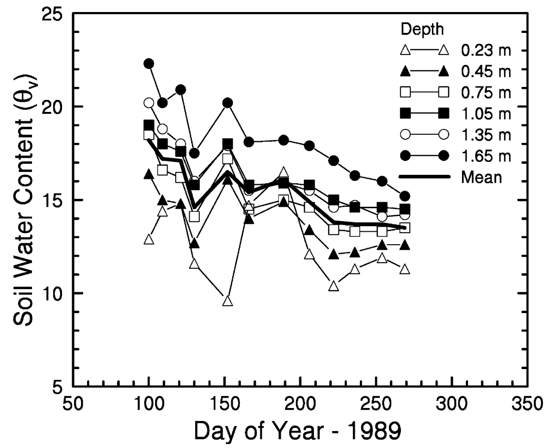

Fig. 6 Soil water content measured in the lysimeter throughout the 1989 growing season. Other information is as given in Fig. 4

Araujo et al. (1995b) reported that water use of 3-year old Thompson Seedless vines was 437 and 517 mm of water for drip- and furrow-irrigated vines between budbreak and harvest at a maximum leaf area per vine of 18.9 and 15.1 m^2, respectively. Our measured ET_c amount during year 3 for drip-irrigated vines between budbreak and harvest was approximately 500 mm, with a maximum leaf area of approximately 13 m^2 per vine. Therefore, ET_c of the drip-irrigated vines in the lysimeter was still greater than estimated by Araujo et al. (1995b) despite similar evaporative demand, the malfunction of the lysimeter from July to the end of the season (i.e. less water was applied than used) and less leaf area per vine. Our maximum daily water use (almost 6 mm per day) in year 3 was three times greater than that reported by Lascano et al. (1992) for 3-year old Chardonnay vines grown in Texas. The Chardonnay vines, however, only had a maximum leaf area of less than 5 m^2 per vine.

The major portion of ET_c during the first year was due to evaporation of water from the soil surface after a furrow-irrigation and the fact that the two vines' canopies were quite small even 6 months after planting (1.4 m^2 leaf area per vine). The amount of water used as ET_c after an irrigation event was comparable to ET_o for

1–3 days following the application of water. Araujo et al. (1995a) concluded that soil evaporation after a vineyard furrow-irrigation event could be 7–8 mm per day. Soil water evaporation estimated in this study on DOY 219 was 5.8 mm [ET_c on DOY 219 (7.0 mm) – ET_c on DOY 218 (1.2 mm) = 5.8 mm]. This value is somewhat less than the soil water evaporation estimated by Araujo et al. (1995a), perhaps due in part to the smaller furrow size used in this study compared with Araujo et al. The daily soil water evaporation values obtained in this study are similar to those determined on bare soils or soils with a sparse canopy by measuring soil moisture depletion with a neutron probe (Lascano and van Bavel 1986; Lascano et al. 1987) or using microlysimeters (Daamen et al. 1993). The patterns of evaporation were consistent with the two distinct phases of the drying process of the soil following an irrigation or significant rainfall event proposed by Hillel (1971) and Ritchie (1972).

The amounts of water lost via soil evaporation for furrow-irrigated vines in a mature vineyard (maximum leaf area of approximately 10 m^2 $vine^{-1}$) have been reported (Yunusa et al. 1997b). Total irrigation amounts during the first and second years of that study were 293 and 321 mm, respectively, while rainfall amounted to 167 mm in the first year and 172 mm in the second. Their estimate of soil water evaporation was equivalent to 274 and 329 mm each year, respectively. Their values of soil evaporation were similar to what we report here as ET_c with similar applied water amounts. Soil evaporation accounted for approximately 50% of estimated ET_c in their study, while we concluded that a minimum of 50% of the ET_c measured in this study during the first year was due to evaporation of water from the soil, with vines having a much smaller leaf area.

From the end of the 1987 growing season throughout the 1988 and 1989 growing seasons, the vines were subsurface drip-irrigated. There are several dates during these two seasons when one could obtain an approximate value of soil surface evaporation. In 1988, ET_c increased from 0.55 to 1.62 mm per day with the first irrigation (2.9 mm of water) of the season (Fig. 3, DOY 144) and the K_c increased from 0.08 to 0.22. The lack of an increase in either ET_c or K_c for the next 30 days and small leaf area per vine (~1.0 m^2) at that time would suggest that increased vine transpiration was not responsible for the initial increase in ET_c. Increasing irrigation amounts from 1.77 mm on DOY 169 to 4.45 mm on DOY 170 increased ET_c from 1.3 to 2.3 mm and the crop coefficient from 0.2 to 0.44. On DOY 170 the 1 mm increase in ET_c was probably due to surface evaporation as the soil surface may have become wetted (See Fig. 4, increased SWC at the 0.23 m depth). In both cases, the soil surface would have been exposed to environmental factors conducive to high evaporation rates (Matthias et al. 1986) due to the low amount of grapevine foliage at that time. The increase in ET_c on both dates of approximately 1 mm was 16% of ET_o. Phene et al. (1993) have shown that bare soil evaporation using subsurface drip-irrigation measured with a lysimeter in western Fresno County, similar to the one used here, was 6% of ET_o.

Another example where soil evaporation from applied water could have been estimated occurred in 1989 for the days prior to DOY 124, 156 and 206. The week that irrigations commenced (beginning with DOY 119) ET_c increased by 2 mm (38% of ET_o) over the previous week despite a minimal increase in evaporative demand and no wetting of the soil surface (Fig. 6). ET_c leveled off thereafter at approximately 3 mm per day. No irrigation for 6 days (between DOYs 150 and 155) reduced ET_c 0.4 mm (6% of ET_o) compared with ET_c the previous week. Reducing the irrigation amount from 5.4 mm per day (for DOYs 194–198) to 2.8 mm per day in the week of DOY 205 (days 199 to 205) reduced ET_c 0.7 mm per day (10% of ET_o). Our estimates of daily soil evaporation using subsurface drip-irrigation were similar to those reported in an Australian vineyard using surface drip-irrigation (Yunusa et al. 1997a). Their estimates of soil evaporation also decreased as the season progressed, as it would appear that ours did.

The primary purpose for the installation of the weighing lysimeter was to establish crop coefficients for grapevines grown in the San Joaquin Valley. Crop coefficients currently used for grapevines are primarily suited for mature vineyards (Doorenbos and Pruitt 1977; Snyder et al. 1987) where growth and canopy characteristics are fairly constant from one year to the next. Seasonal leaf area development and maximum leaf area per vine differs among years during vineyard establishment (Araujo and Williams 1988; Araujo et al. 1995b). Results from those studies, together with leaf area measured in this study, demonstrated that canopy development varies markedly from the first through the third year of vine establishment, affecting vine water use and crop coefficients.

The initial use of furrow-irrigation after planting made it difficult to establish seasonal K_c values for these first-year vines. A second-order polynomial regression using all the data points in Fig. 1 (data not shown) resulted in a K_c of 0.35 at planting and a K_c of 0.4 at the end of September. We feel that the regression run through the lowest calculated K_cs in Fig. 1 ('basal K_c'), however, would be appropriate for drip-irrigated vines. The fitted K_c curve for the second growing season (Fig. 2) reflected the lack of significant canopy early in the growing season when a single shoot was trained up the trellis stake to form the trunk and then growth (from lateral shoots) as the head was established. The continued shoot growth late in the season, with little leaf senescence, and the lack of a crop was probably responsible for the K_c not decreasing until well into November. Published crop coefficients for mature vines, those producing a crop, decrease once harvesting has taken place (Doorenbos and Pruitt 1977; Snyder et al. 1987). A curve similar to that derived in the second year was used to describe the seasonal progression of the K_c during year 3. It reflects the earlier development of the vines' canopies in year 3, compared with year 2, and a higher maximum K_c. It is felt that the marked decline in the K_c during July in year 3 would not have occurred if the lysimeter had functioned properly. Therefore, the fitted curve (Fig. 5) reflects our assumption that vine water use would have resulted in a constant value of the K_c until well into October, similar to that in year 2.

Conclusions

Data collected in this study demonstrated that surface evaporation using furrow-irrigation was at least 50% of ET_c during the first year of vineyard establishment. Much of the rainfall early in the growing season, a time when the vine canopies were small during years 2 and 3, was also lost to evaporation under the conditions of the study. The 'basal K_c' the first year of the study ranged from 0.1 early on to 0.4 at the end of the season. The seasonal K_c during the second growing season increased up until late in the growing season, at which time it appeared to level off at a value of 0.7. The seasonal K_c in 1989 increased from 0.1 to greater than 0.8 (from budbreak until the lysimeter malfunction at mid-season). It is unknown whether the precipitous drop in vine water use mid-season that year and the lack of increased water use after irrigations resumed were due to severe vine stress or to the amount of water subsequently applied by the lysimeter.

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