Irrig Sci (2003) 22: 11–18
DOI 10.1007/s00271-003-0067-5

ORIGINAL PAPER

L. E. Williams · C. J. Phene · D. W. Grimes · T. J. Trout

Water use of mature Thompson Seedless grapevines in California

Received: 20 May 2002 / Accepted: 14 January 2003 / Published online: 18 March 2003

Abstract Water use of Thompson Seedless grapevines was measured with a large weighing lysimeter from 4 to 7 years after planting (1990–1993). Above-ground drip-irrigation was used to water the vines. Vines growing within the lysimeter were pruned to four and six fruiting canes for the 1990 and 1991 growing seasons, respectively, and eight fruiting canes in the last 2 years. Maximum leaf area per vine at mid-season ranged from 23 to 27 m^2 across all years. Reference crop evapotranspiration (ET_o) averaged 1,173 mm between budbreak and the end of October each year, with a maximum daily amount of approximately 7 mm each year. Maximum daily vine water use (ET_c) was 6.1, 6.4, 6.0, and 6.7 mm (based upon a land area per vine of 7.55 m^2) for 1990, 1991, 1992, and 1993, respectively. Seasonal ET_c was 718 mm in 1990 and ranged from 811 to 865 mm for the remaining 3 years of the study. The differences in water use among years were probably due to the development of the vine's canopy (leaf area), since they were pruned to differing numbers of fruiting canes. These differences were more pronounced early in the season. Soil water content (SWC) within the lysimeter decreased early in the growing season, prior to the initiation of the first irrigation. Once irrigations commenced, SWC increased and then leveled off for the remainder of the season. The maximum crop coefficient (K_c) calculated during the first year (1990) was 0.87. The maximum K_c in 1991, 1992, and 1993 was 1.08, 0.98, and 1.08, respectively. The maximum K_c in 1991 and 1993 occurred during the month of September, while that in 1992 was recorded during the month of July. The seasonal K_c followed a pattern similar to that of grapevine leaf area development each year. The K_c was also a linear function of leaf area per vine using data from all four growing seasons. The decrease in K_c late in the 1991, 1992, and 1993 growing seasons, generally starting in September, varied considerably among the years. This may have been associated with the fact that leafhoppers (*Erythroneura elegantula* Osborn and *E. variabilis* Beamer) were not chemically controlled in the vineyard beginning in 1991.

L. E. Williams (✉)
Department of Viticulture and Enology, University of California—Davis and Kearney Agricultural Center, 9240 S. Riverbend Ave., Parlier, CA 93648, USA
E-mail: williams@uckac.edu

D. W. Grimes
Department of Land, Air and Water Resources, University of California—Davis and Kearney Agricultural Center, 9240 S. Riverbend Ave., Parlier, CA 93648, USA

C. J. Phene · T. J. Trout
Water Management Research Laboratory, USDA-ARS, Parlier, CA 93648, USA

Present address: C. J. Phene
SDI, PO Box 314, Clovis, CA 93611, USA

Introduction

Seasonal water use of mature grapevines has been measured in several studies using various methods (Evans et al. 1993; Grimes and Williams 1990; Peacock et al., 1987; Prior and Grieve 1987; van Rooyen et al. 1980; van Zyl and van Huyssteen 1980, 1988; Williams and Matthews 1990; Yunusa et al. 1997a, 1997b). Results from the aforementioned studies indicate that vineyard water use varies considerably. It is unknown, however, how much of the variability from vineyard to vineyard reported above is the result of differences in production practices or the method of determining vine water use.

A weighing lysimeter was installed near Fresno in the San Joaquin Valley of California to directly measure evapotranspiration (ET_c) of grapevines. Thompson Seedless grapevines were planted in the lysimeter in 1987 and results from the first 3 years of growth are presented in a previous paper (Williams et al. 2003). This paper will report on vine water use from year 4 to year 7 after planting (four cropping seasons). In addition, daily and diurnal vine water use will be presented. Lastly, seasonal crop coefficients (K_c) were developed in order to provide the information necessary to schedule irrigations in vineyards similar to the one used in the study.

Materials and methods

The weighing lysimeter at the University of California Kearney Agricultural Center, containing two *Vitis vinifera* L. (cv. Thompson Seedless) grapevines, as described in the preceding paper (Williams et al. 2003), was used in this study. The data presented herein were collected from 1990 to 1993. Technical aspects of measuring vine water use (ET_c) were similar to those previously given, as was the source of reference crop evapotranspiration (ET_o) data and calculation of degree-days (DDs).

Vines in the lysimeter were irrigated with 4 l h^{-1} in-line drip emitters, spaced every 0.30 m. The drip tubing was attached to a wire suspended 0.4 m above the soil surface. This differs from the two previous years (1988 and 1989), as subsurface drip-irrigation was used (Williams et al. 2003). The number of irrigations per day throughout the 1990 to 1993 growing seasons ranged from 0 to 7.

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 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 vines in the surrounding vineyard (7.55 m^2 of surface area), once irrigations had commenced, by multiplying by 0.53. It was assumed that soil water evaporation in the area outside the lysimeter was minimal. Estimates of soil water evaporation (using the neutron probe) midway between rows in 1992 ranged from 0.26 mm day^{-1} at the end of May to 0.09 mm day^{-1} in the second week of September.

Leaf area of vines within the lysimeter was estimated using non-destructive methods (Williams et al. 2003). Once the measurements of shoots on the lysimeter-grown vines became too difficult, the leaf area of vines in the vineyard surrounding the lysimeter were destructively determined and the values were assumed to be representative of the lysimeter vines. Pruning weights (a measure of vegetative growth) and yields measured on the two vines within the lysimeter during each year of the study were similar to vines growing in the surrounding vineyard.

Vines were pruned to four fruiting canes for the 1990 growing season, six canes for the 1991 growing season and eight canes for the 1992 and 1993 growing seasons. Standard horticultural practices to control disease and insect pests of grapevines were performed as needed by field station personnel each year. No pesticides were used to control western grape (*Erythroneura elegantula* Osborn) or variegated (*E. variabilis* Beamer) leafhoppers, however, during the 1991 through 1993 growing seasons.

Results

Rainfall amounts varied considerably among water years (from 1 November the previous year to 31 October in the present year) and the amount that fell during each growing season (from date of budbreak until the end of October) (Table 1). In most years, the majority of in-season rainfall occurred during March, the month in which budbreak normally takes place for Thompson Seedless grapevines at this location (Table 2).

The record amount of rainfall that fell during 1993 was reflected in the high soil water content measured within the lysimeter early in the season, compared with the other years (Fig. 1). The 1993 season was the first time that water drained from the lysimeter. Irrigations generally commenced prior to anthesis, the last week in April to the first week in May each year (Table 2). Prior to that date, soil water content decreased. Once irrigations were initiated, soil water content increased and then leveled off and remained relatively constant until the last measurement date of the season (Fig. 1). The seasonal pattern and absolute amounts of soil water content for vines in the vineyard surrounding the lysimeter receiving the same amounts of water were similar to those within the lysimeter (unpublished data). The decrease in soil water content in 1990 between days of year (DOYs) 125 and 160 was associated with a period

Table 1 Total rainfall from 1 November (the previous year) to budbreak (BB) and rainfall amounts and their date of occurrence between budbreak and 31 October during the 1990, 1991, 1992 and 1993 growing seasons at the Kearney Agricultural Center, California

Growing season	Calendar date	Day of year	Rainfall (mm)
1990	1 November (1989): BB		128
	4 April	93	2
	23 April	113	21
	23 May	143	7
	28 May[a]	148	27
	8 August	220	4
1991	1 November (1990): BB		162
	17 March	76	25
	18 March	77	31
	19 March	78	11
	20 March	79	9
	24 March	83	9
	25 March	84	6
	26 March	85	7
	27 March	86	2
	1 April	91	2
	26 October	299	16
1992	1 November (1991): BB		241
	14 March	74	5
	30 March	90	8
	12 April	103	3
	2 May	123	15
1993	1 November (1992): BB		350
	13 March	72	4
	17 March	76	5
	25 March	84	32
	28 March	87	9
	4 April	94	2
	17 April	107	2
	23 May	143	3
	5 June[a]	156	5

[a] The amounts for these two dates include rain that fell on the previous day

Table 2 Dates of budbreak, initiation of irrigation, harvest and the accumulation of degree-days from budbreak to 31 October measured each year of the study. Degree-days were obtained from the University of California Statewide Integrated Pest Management Project using a base temperature of 10°C

Year	Date of budbreak	Date of 1st irrigation	Date of harvest	Degree-day accumulation
1990	18 March	27 April (117)[a]	27 August (239)[a]	2,564
1991	15 March	8 May (128)	22 September (265)	2,475
1992	14 March	8 May (129)	4 September (248)	2,728
1993	10 March	3 May (123)	21 September (263)	2,486

[a] Day of year is in parenthesis

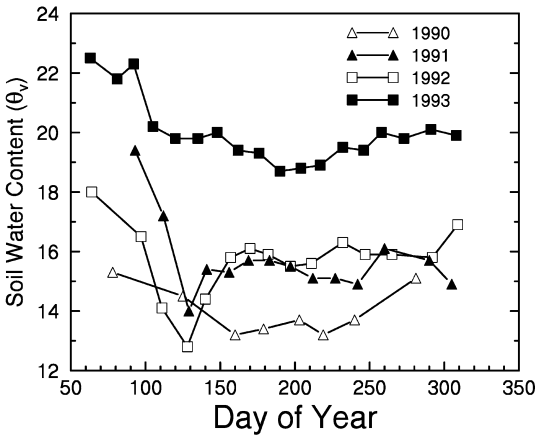

Fig. 1 Soil water content (expressed as percent by volume: θ_v) measured in the lysimeter during each growing season of the study. An individual data point is the average of two access tubes measured at six depths (from 0.23 to 1.65 m below the soil surface)

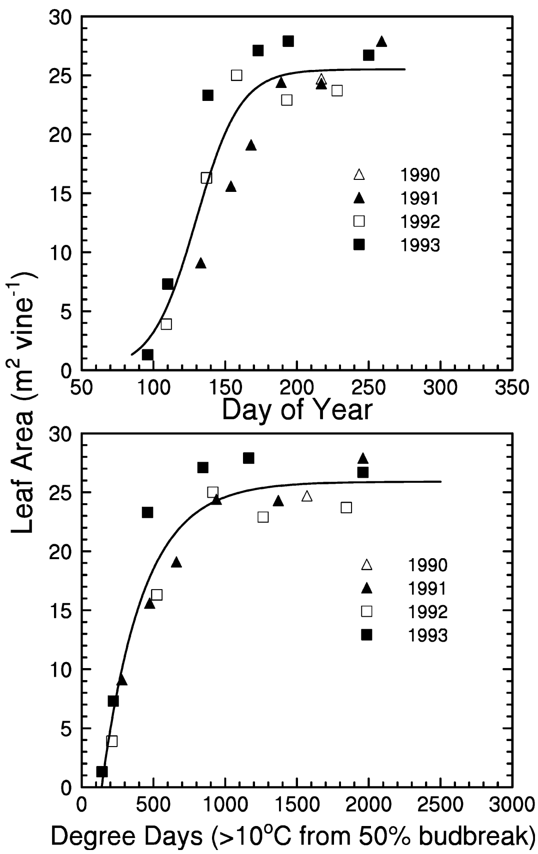

Fig. 2 Leaf area development of Thompson Seedless grapevines as a function of day of year (*DOY*) and degree-days (*DDs*) measured from budbreak over the course of the study. The dependent variable of the equations (x) represents DOY and DDs, respectively, for the top and bottom portions of the figure. The equations used to describe leaf area as a function of DOY and DDs were: $y = 25.5/(1 + e^{(-(x - 130)/15.5)})$, $R^2 = 0.86$ and $y = -16.1 + 42.0(1 - e^{(-(0.00347)x)})$, $R^2 = 0.92$, respectively

in which the vines within the lysimeter were not irrigated (between DOYs 147 and 153) and due to rainfall on DOYs 143 and 148.

Table 3 Reference crop evapotranspiration (ET_o) and water use (ET_c) measured each year of the study from budbreak until the end of October. Water use in liters per vine was that directly measured by the lysimeter, while water use in millimeters was direct lysimeter water use divided by area per vine in the vineyard. Reference crop ET data were obtained from the CIMIS (number 39) weather station at the Kearney Agricultural Center, California

Year	ET_o (mm)	ET_c (l vine^{-1})	ET_c (mm)
1990	1,209	5,418	718
1991	1,188	6,532	865
1992	1,170	6,123	811
1993	1,124	6,472	857

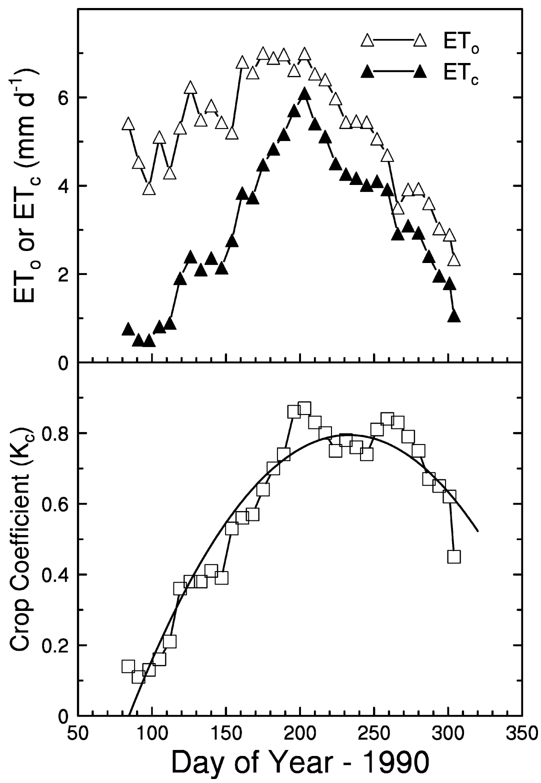

Fig. 3 The seasonal progression of daily water use (ET_c), measured with a weighing lysimeter in 1990, reference crop evapotranspiration (ET_o) and crop coefficients (K_c) as a function of Day of Year (*DOY*). Each *data point* is the average daily value for a 7-day period. The seasonal K_c values were fitted to the following equation: $y = -1.16 + 0.0168x - 0.000036x^2$, $R^2 = 0.92$

The maximum estimated leaf area per vine at full canopy ranged from 23 to 27 m^2 vine^{-1} across all seasons (Fig. 2). This was despite the fact that vines had been pruned to different numbers of fruiting canes in the first 3 years. Leaf area development (LAD) in 1991 appeared to lag behind LAD in 1992 and 1993 when plotted as a function of DOY, but there was no such lag when leaf area was plotted versus degree-days (DDs).

Reference crop ET (ET_o) from budbreak until the end of October each year ranged from 1,124 to 1,209 mm (Table 3). There was generally a large variability in ET_o early in the growing season, resulting from

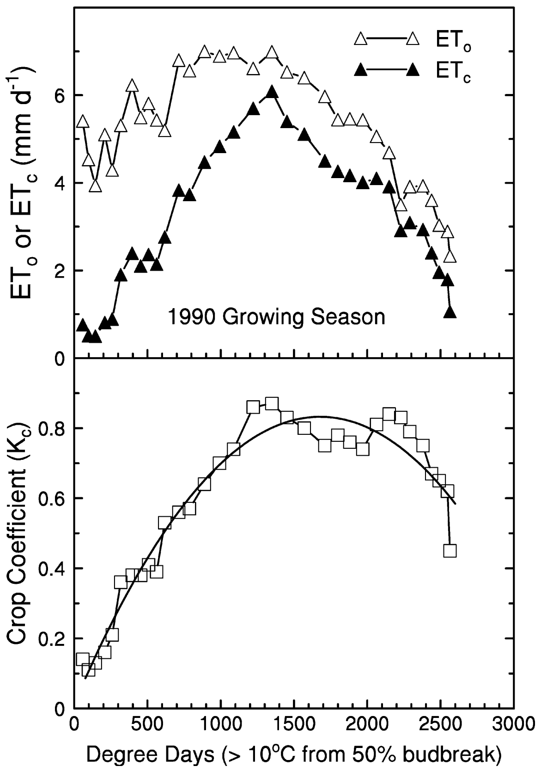

Fig. 4 The seasonal progression of daily ET_c, ET_o and K_c measured in 1990 as a function of degree-days from date of budbreak. Each *data point* is the average daily value for a 7-day period. The seasonal K_c values were fitted to the following equation: $y = 0.0129 + 0.000377x - 0.000000291x^2$, $R^2 = 0.95$

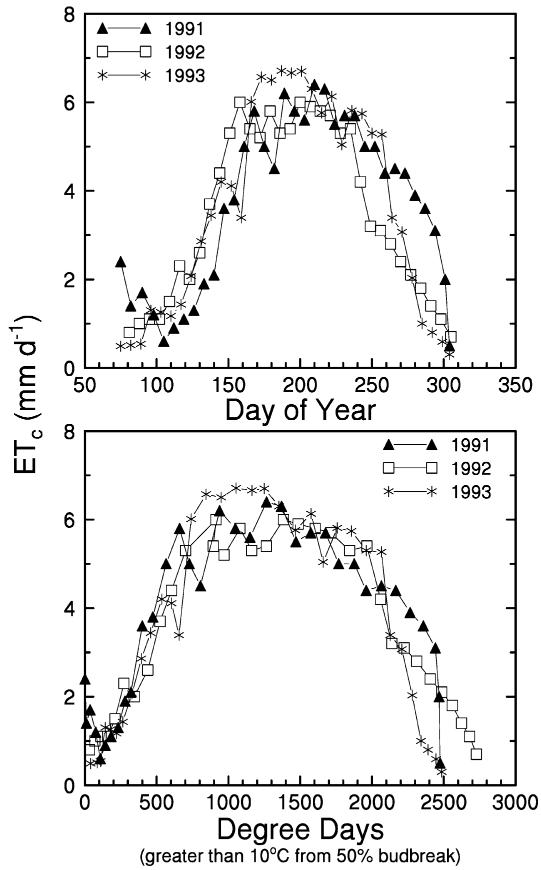

Fig. 5 The seasonal progression of daily water use (ET_c) measured during the 1991, 1992, and 1993 growing seasons with a weighing lysimeter. Seasonal ET_c as a function of day of year (*DOY*) and degree-days (*DDs*) were fitted to quadratic equations with: $ET_c = -11.05 + 0.1665*DOY - 0.000417*DOY^2$; $R^2 = 0.78$; $ET_c = 0.182 + 0.0088*DD - 0.000003302*DD^2$, $R^2 = 0.88$. Other information is as given in Fig. 3

cloud cover and/or rainfall events. Maximum daily ET_o, using a 7-day running average, was approximately 7 mm each year (illustrated in Fig. 3).

Grapevine water use increased from less than 0.5 mm per day on DOY 100 in 1990 to more than 2 mm per day by DOY 130 (Figs. 3 and 4). Step increases in ET_c on DOYs 113 and 150 were due to temporary increased soil evaporation associated with rainfall events (Table 1). The maximum ET_c of the season occurred in mid-July when leaf area was 24.4 m^2 vine^{-1} and evaporative demand was highest. At this time shoots of the vines were hedged (to facilitate the movement of equipment down the row) removing 4.1 m^2 of leaf area per vine. The decrease in ET_c after this date was due to a reduction in canopy and/or a reduction in ET_o (Fig. 3). The crop coefficient (K_c) for 1990 reached a maximum of 0.87, coinciding with maximum leaf area, and then oscillating between 0.74 and 0.84 until the end of September (DOY 275). The K_c declined to 0.45 by the end of October. The seasonal K_c values for 1990 expressed as a function of both DOY (Fig. 3) and DDs (Fig. 4) were fitted to quadratic equations with the fit being rather better when using DDs.

The seasonal course of ET_c from 1991 to 1993 was similar, with the greatest values of ET_c (almost 50 l day^{-1} or approximately 6.6 mm day^{-1}) occurring during the period between 23 June (DOY 174) and 20 July (DOY 201) in 1993 (Fig. 5). Maximum hourly water use at midday during that time period ranged from 0.82 to 0.95 mm h^{-1} (6.2 to 7.1 l h^{-1}). The daily course of ET_c measured with the lysimeter closely followed that of ET_o and net radiation (Fig. 6). There appeared to be less variability in the seasonal progression of ET_c among years when it was expressed as a function of DDs from budbreak rather than using DOY in this study. ET_c decreased more rapidly in 1992 and 1993 than in 1991 when expressed as a function of DOY but less so when expressed as a function of DDs. The decrease in ET_c did not appear to be related to date of harvest (Table 2), as harvest did not occur in 1992 until 2 weeks after the large decline in ET_c that year.

Seasonal water use in 1990 was 718 mm (5,400 l vine^{-1}) from budbreak until the end of October (Table 3). This was approximately 60% of ET_o during that time frame. Vine water use between budbreak to end of October for the next 3 years were similar and averaged 844 mm per year (6,375 l vine^{-1}), that value being approximately 73% of average ET_o.

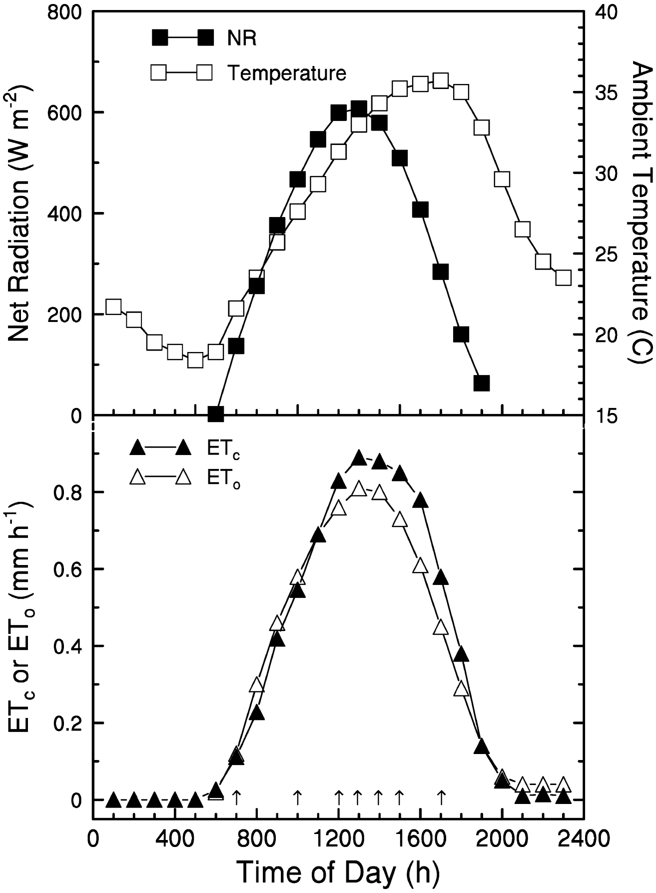

Fig. 6 The daily time course of Thompson Seedless water use on 7 July 1993 measured with a weighing lysimeter. Values of hourly net radiation (*NR*), ambient temperature (*T*) and reference crop evapotranspiration (ET_o) were obtained from the CIMIS weather station at the Kearney Agricultural Center. Net radiation values less than zero were not included. Values of water use (ET_c) were expressed on an area basis of 7.55 m^2. *Arrows at the bottom* indicate an irrigation event

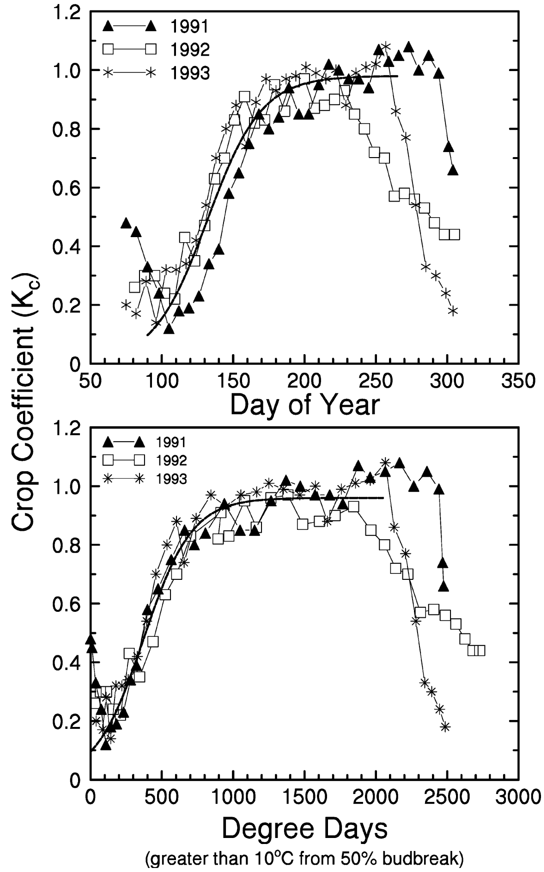

Fig. 7 The seasonal progression of the crop coefficient for Thompson Seedless grapevines calculated for the 1991, 1992, and 1993 growing seasons. The K_c as a function of day of year (*DOY*) and degree-days (*DDs*) were fit to the following equations: $y = 0.98/(1 + e^{(-(x - 132)/19)})$, $R^2 = 0.85$ and $y = 0.96/(1 + e^{(-(x - 373)/169)})$, $R^2 = 0.92$, respectively. The *first three data points* of each year and those data points where the K_c started to decline precipitously later in the growing season were not used to generate the equation for both DOY and DDs (total $n = 69$: $n = 26$, 20, and 23 in 1991, 1992, and 1993, respectively). Other information is as given in Fig. 3

Once early-season rainfall had subsided, the seasonal K_c increased almost linearly when plotted either as a function of DOY or DDs (Fig. 7). The maximum K_c was 1.08 in 1991 and 1993 late in the growing season and 0.98 in July (DOY 200) of 1992. A decline in the K_c from a value of 1.0 did not occur until the third week of October in 1991. In 1992 there was a more gradual decline in the K_c, starting at the end of August (DOY 235). There was a steep drop in the K_c during the week of 16 September (DOY 258) in 1993, after reaching its highest value of the season.

The K_c values shown within Fig. 7 were fitted to a sigmoid-type equation with three parameters when expressed as a function of DOY and DDs. High K_c values due to rainfall early in each growing season and the K_c values late in the season, once they started to decline, were not used to generate these equations. The prediction of the seasonal K_c using quadratic equations for both DOY and DDs resulted in R^2 values less than for the sigmoid-type equations ($K_c = -1.184 + 0.01879*DOY - 0.00004623*DOY^2$, R^2 =

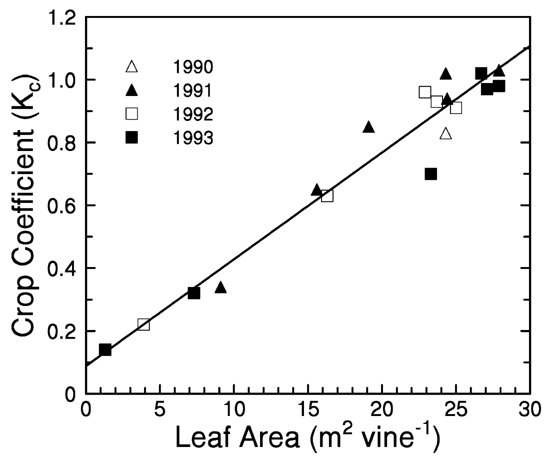

Fig. 8 The relationship between crop coefficient (K_c) and leaf area of Thompson Seedless grapevines calculated over the course of four growing seasons. Leaf area was estimated several times during each growing season. The crop coefficients used in this figure were those calculated for the week that leaf area was determined. Data were fit to the following equation: $y = 0.088 + 0.034x$, $R^2 = 0.94$

0.66; $K_c = 0.1594 + 0.001148*DD - 0.0000003939*DD^2$, $R^2 = 0.78$, respectively). A cubic equation did not improve the R^2 values for the K_c as a function of DOY or DDs. Lastly, the K_c was a linear function of leaf area per vine using data from all 4 years (Fig. 8).

Discussion

The ET_c values measured in this lysimeter study are greater than those reported in several other studies conducted in mature vineyards using different cultivars (Erie et al. 1982; Evans et al. 1993; Oliver and Sene 1992; Saayman and Lambrechts 1995; van Rooyen et al. 1980; van Zyl and van Huyssteen 1980), Thompson Seedless in California (Peacock et al. 1987) and Sultana (syn. Thompson Seedless) in Australia (Yunusa et al. 1997a, 1997b). Our water-use values, however, are similar to those of Grimes and Williams (1990) using Thompson Seedless grown in California and Prior and Grieve (1987) using Sultana grown in Australia. The differences in water use between our study and some of the others cited above are probably due to differences in production practices such a pruning level, trellis size, canopy management practices involving leaf removal, irrigation type and frequency, and prevailing climatic conditions. On the other hand, some of the studies used techniques that are based upon assumptions that may detract from their accuracy, whereas in this study the lysimeter directly measured ET_c. In addition, the high frequency with which the vines in the lysimeter were irrigated (water applied whenever 16 l had been used) resulted in vines that would not have been stressed at any time throughout the growing season. This was confirmed by measurements of midday leaf water potential (Williams et al. 1994).

Maximum daily ET_c in this study was approximately 6.6 mm (50 l per vine) and this occurred when ET_o was 7 mm day^{-1}. Leaf area per vine at this time was in excess of 27 m^2. There are only a few studies where daily grapevine ET_c has been measured or estimated. Stevens and Harvey (1996) reported a maximum daily ET_c of 13.6 mm (119 l $vine^{-1}$) at an ET_o of 11.6 mm for Colombard grapevines grown in Australia and irrigated with full cover microjets. Those vines had a maximum leaf area of 24 m^2 $vine^{-1}$. Daily ET_c of drip-irrigated Sultana grown in Australia approached a maximum of only 3 mm, or approximately 25 l per vine (Yunusa et al. 1997a). Using data presented in the Yunusa et al. (1997a) paper, we calculated that the Sultana vines had a maximum leaf area of 26.8 m^2. Lastly, Heilman et al. (1996) reported a maximum daily ET_c of 5.1 mm (26 l $vine^{-1}$) for Chardonnay grapevines (7.1 m^2 leaf area) grown in Texas and that vine transpiration accounted for 82% of ET_c. Even if the data in the above studies were normalized to a per leaf area basis, there would still be large differences among maximum rates of daily vine water use.

The weighing lysimeter measured ET_c on an hourly basis and there are just a few studies in which comparisons can be made. The use of sap-flow sensors has recently been used to measure transpiration of grapevines and daily and hourly transpiration values have been published (Eastham and Gray 1998; Heilman et al. 1994, 1996; Lascano et al. 1992). Maximum flux density of latent heat in a Chardonnay vineyard in Texas on a diurnal basis was approximately 300 W m^{-2} while that of the canopy (using a sap-flow sensor) was 100 W m^{-2} (Heilman et al. 1994). The maximum flux density on a diurnal basis reported here (Fig. 6) was approximately 600 W m^{-2}. It is doubtful that our value of vineyard latent heat was predominated by soil evaporation, as found in the study by Heilman et al. (1994) since, at the time our measurements were made, the canopy shaded all of the wetted area of the soil beneath the drip line. In a subsequent study, Heilman et al. (1996) determined that more than 80% of the total daily latent heat flux of a vineyard with an open hedgerow canopy (which increased solar radiation interception when compared with Heilman et al. 1994) was due to vine transpiration. This value is similar to estimates by Ayars et al. (2003) with peach trees.

Maximum hourly transpiration of Maroo Seedless grapevines having 13.4 m^2 of leaf area in Australia was greater than 0.4 l h^{-1} (Eastham and Gray 1998). While the leaf area of the Thompson Seedless grapevines used in this study were double that of the Maroo Seedless, maximum hourly ET_c in Fig. 6 was 16 times greater. It was also six times greater when the two are expressed as a function of water use per square meter of leaf area per hour (0.03 l m^{-2} h^{-1} for Maroo Seedless and 0.19 l m^{-2} h^{-1} for Thompson Seedless). Even if soil evaporation accounted for 20% of ET_c in this study our hourly values would still be considerably greater than that for Maroo Seedless. Recently it has been demonstrated that sap-flow sensors may underestimate transpiration on vines with large trunks (Tarara and Ferguson 2001), which may have been the case in the Maroo Seedless study.

The K_c relates ET of a crop under optimum soil water conditions to that of ET_o (Doorenbos and Pruitt 1977). It has been demonstrated that grapevine ET_c/ET_o (Stevens and Harvey 1996) or ET_c/Class A pan evaporation (van Zyl and van Huyssteen 1980) decreases linearly once soil water content decreases below field capacity. The purpose of irrigating the vines within the lysimeter whenever they had used 16 l of water was to insure that water was not limiting vine transpiration. It is interesting that mean soil water content within the lysimeter varied among the 4 years, the driest in 1990 and wettest in 1993, but that maximum water use and K_c were similar at comparable canopy size. The high frequency irrigation used here, even in 1990, would have maintained at least a portion of the soil profile close to field capacity. Phene et al. (1989) have clearly demonstrated this principle with field crops using similar weighing lysimeters.

The seasonal progression of ET_c and K_c reported here reflects the increase in canopy size early in the season up to a maximum, at which time the hedging of shoots maintained the vines' leaf area fairly constant from that point on. The maximum leaf area estimated for the vines in the lysimeter were similar to those determined in previous studies for this cultivar (Williams 1987a, 1996; Williams and Matthews 1990). We also found that the K_c was a linear function of the leaf area from shortly after budbreak until August. Ayars et al. (2003) found that the K_c was a linear function of the amount of light intercepted by peach (*Prunus persica* L.) trees. It could be assumed that as leaf area increases so would the amount of solar radiation intercepted by our grapevines and the amount of ET_c. The maximum shaded area beneath the vine's canopy at midday in this study was estimated to be approximately 60% of the total land area per vine at which time a K_c of 1.0 was measured. This K_c is similar to that reported by Ayars et al. (2003) when solar radiation interception of the peach trees was 60%.

The seasonal progression of the K_c reported here is similar to that used by others for grapevines grown either in California or elsewhere (Doorenbos and Pruitt 1977; Grimes and Williams 1990; Snyder et al. 1987). This pattern differs from those developed for grapevines grown in the state of Washington (Evans et al. 1993) where the K_c increases more slowly early on, reaches a maximum for a short period and decreases dramatically well before harvest. The maximum K_c values we calculated here were very close to or in excess of 1.0. The maximum K_c reported by Stevens and Harvey (1996) was close to 1.2. Doorenbos and Pruitt (1977) suggested a maximum K_c of 0.75 for vines similar to those used in this study while Grimes and Williams (1990) and Snyder et al. (1987) reported 0.8 as their maximum K_c. The maximum K_c for the lysimeter grown vines was more than double that (0.41) used in a study by Peacock et al. (1987) for Thompson Seedless grapevines grown in the San Joaquin Valley. Peacock et al. (1987) though, calculated the K_c to be a fraction (0.75) of the percent shaded area measured beneath the vine at midday. The maximum shaded area in that study was 55% ($0.55 \times 0.75 = 0.41$). The crop coefficient is dependent upon numerous factors, one of these being variations in soil evaporation depending upon irrigation type and frequency (Jagtap and Jones 1989). The differences in the above maximum K_c value at midseason reported in this study and those also used for Thompson Seedless in the San Joaquin Valley (Grimes and Williams 1990; Peacock et al. 1987) may be due to differences in irrigation frequency and/or scheduling and possibly the method with which ET_c was determined.

The quadratic equation used to calculate seasonal K_c values by Grimes and Williams (1990) would overestimate vine ET in this study early in the growing season for all years studied (1990–1993) and underestimate vine ET late in the growing season. While a quadratic function would fit our seasonal K_c values adequately, it is felt that sigmoid type equations, similar to those used to describe the development of leaf area would be more appropriate to describe our seasonal K_c values either as a function of DOY or DDs. In fact, the linear fit method to calculate the K_c used by Allen et al. (1998) and Snyder et al. (1987) could also be adapted to our seasonal K_c, at least up until late in the growing season. While there was a decrease in the K_c values toward the end of each growing season here, it varied considerably from year to year. As mentioned previously, leafhoppers (*Erythroneura elegantula* Osborn and *E. variabilis* Beamer) were not chemically controlled, beginning with the 1991 growing season, due to a study being conducted in the vineyard surrounding the lysimeter. Just prior to and subsequent to harvest, the third brood generally reaches its peak population numbers. Feeding on grapevine leaves by leafhoppers can decrease stomatal conductance (L.E. Williams, unpublished data) and, at high enough populations, vines can be defoliated. It appeared that, as the years progressed, the populations within the vineyard increased considerably so that by 1993 a precipitous drop in the K_c was due to defoliation. In subsequent years, when leafhoppers were controlled, the K_c remained constant from mid-season up until the end of October (unpublished data).

The use of DDs to plot the seasonal K_c may be better than using DOY. It was shown in this study and elsewhere that leaf area development (Williams 1987a) and phenology (Williams 1987b) of Thompson Seedless grapevines are highly correlated with DDs. The use of DDs would also eliminate early-season variability in vine growth due to weather conditions. Crop coefficients developed at the Kearney Agricultural Center with the weighing lysimeter have been used successfully in the Coachella Valley of southern California to schedule irrigations where budbreak occurs 2 months prior to that in the Fresno area (L.E. Williams, unpublished data). This was accomplished by calculating the K_c as a function of DDs from budbreak for three different cultivars.

Conclusions

The daily water use of high frequency, above-ground, drip-irrigated Thompson Seedless grapevines grown in the San Joaquin Valley of California peaked at values greater than 50 l vine^{-1} (6.6 mm), while seasonal water use was greater than 800 mm the last 3 years of the study. The seasonal water use was 60% of ET_o in 1990 and was 73% of ET_o for the remainder of the study. The maximum K_c calculated in this study was greater than 1. This occurred when leaf area per vine was generally greater than 25 m^2. The K_c was also a linear function of leaf area per vine. The use of degree-days (DDs) was somewhat more useful in predicting the K_c than day of year (DOY).

Acknowledgements The authors would like to thank P.J. Biscay, P. Wiley, R.M. Mead and D.A. Clark for their assistance in this study. We also thank Drs. J. Ayars and D. Bryla for their review of the manuscript.Mention of trade names or proprietary products is for the convenience of the reader only and does not constitute endorsement or preferential treatment by the University of California or USDA/ARS.

References

Allen RA, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. (FAO irrigation and drainage paper 56) FAO, Rome

Ayars JE, Johnson RS, Phene CJ, Trout TJ, Clark DA, Mead RM (2003) Water use by drip irrigated late season peaches. Irrig Sci (in press)

Doorenbos J, Pruitt WO (1977) Crop water requirements. (FAO irrigation and drainage paper 24) FAO, Rome

Eastham J, Gray SA (1998) A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation. Am J Enol Vitic 49:171–176

Erie LJ, French OF, Bucks DA, Harris K (1982) Consumptive use of water by major crops in the southwestern United States. (Conservation research report no. 29) United States Department of Agriculture, Washington. D.C.

Evans RG, Spayd SE, Wample RL, Kroeger MW, Mahan MO (1993) Water use of *Vitis vinifera* grapes in Washington. Agric Water Manage 23:109–124

Grimes DW, Williams LE (1990) Irrigation effects on plant water relations and productivity of Thompson Seedless grapevines. Crop Sci 30:255–260

Heilman JL, McInnes KJ, Savage MJ, Gesch RW, Lascano RJ (1994) Soil and canopy energy balances in a west Texas vineyard. Agric For Meteor 71:99–114

Heilman JL, McInnes KJ, Gesch RW, Lascano RJ, Savage MJ (1996) Effects of trellising on the energy balance of a vineyard. Agric For Meteor 81:79–93

Jagtap SS, Jones JW (1989) Stability of crop coefficients under different climate and irrigation management practices. Irrig Sci 10:231–244

Lascano RJ, Baumhardt RL, Lipe WN (1992) Measurement of water flow in young grapevines using the stem heat balance method. Am J Enol Vitic 43:159–165

Oliver HR, Sene KJ (1992) Energy and water balances of developing vines. Agric For Meteorol 61:167–185

Peacock WL, Christensen LP, Andris HL (1987) Development of a drip irrigation schedule for average-canopy vineyards in the San Joaquin Valley. Am J Enol Vitic 38:113–119

Phene CJ, McCormick RL, Davis KR, Pierro J, Meek DW (1989) A lysimeter feedback controller system for evapotranspiration measurements and real time irrigation scheduling. Trans ASAE 32:477–484

Prior LD, Grieve AM (1987) Water used and irrigation requirements of grapevines. In: Lee T (ed) Proceedings of the 6th Australian Wine Industry Technical Conference, 14–17 July, Adelaide. Australian Industrial Publications, Adelaide, pp 165–168

Rooyen FC van , Weber HW, Levin I (1980) The response of grapes to a manipulation of the soil–plant–atmosphere continuum. II. Plant–water relationships. Agrochemophysica 12:69–74

Saayman D, Lambrechts JJN (1995) The effect of irrigation system and crop load on the vigour of Barlinka table grapes on a sandy soil, Hex River Valley. S Afr J Enol Vitic 16:26–34

Snyder RL, Lanini BJ, Shaw DA, Pruitt WO (1987) Using reference evapotranspiration (ET_o) and crop coefficients to estimate crop evapotranspiration (ET_c) for trees and vines. (UC leaflet 21428) University of California, Division of Agriculture and Natural Resources, Berkeley, Calif.

Stevens RM, Harvey G (1996) Soil water depletion rates under large grapevines. Aust J Grape Wine Res 2:155–162

Tarara JM, Ferguson JC (2001) Device for simulating high rates of sap flow in grapevines. Am J Enol Vitic 52:260–265

Williams LE (1987a) Growth of 'Thompson Seedless' grapevines. I. Leaf area development and dry weight distribution. J Am Soc Hortic Sci 112:325–330

Williams LE (1987b) The effect of cyanamide on budbreak and vine development of Thompson Seedless grapevines in the San Joaquin Valley of California. Vitis 26:107–113

Williams LE (1996) Grape. In: Zamski E, Schaffer AA (eds) Photoassimilate distribution in plants and crops: source–sink relationships. Marcel Dekker, New York, pp 851–881

Williams LE, Matthews MA (1990) Grapevines. In: Stewart BA, Nielsen DR (eds) Irrigation of agricultural crops. (ASA monograph no 30) ASA-CSSA-SSSA, Madison Wis., pp 1019–1055

Williams LE, Dokoozlian NK, Wample R (1994) Grape. In: Schaffer B, Anderson PC (eds) Handbook of environmental physiology of fruit crops. Vol I: temperate crops. CRC, Boca Raton, Fla., pp 85–133

Williams LE, Phene CJ, Grimes DW, Trout TJ (2003) Water use of young Thompson Seedless grapevines in California. Irrig Sci: DOI 10.1007/s00271-003-0066-6

Yunusa IAM, Walker RR, Blackmore DH (1997a) Characterisation of water use by Sultana grapevines (*Vitis vinifera* L.) on their own roots or on Ramsey rootstock drip-irrigated with water of different salinities. Irrig Sci 17:77–86

Yunusa IAM, Walker RR, Guy JR (1997b) Partitioning of seasonal evapotranspiration from a commercial furrow-irrigated Sultana vineyard. Irrig Sci 18:45–54

Zyl JL van, Huyssteen L van (1980) Comparative studies on wine grapes on different trellising systems: I. Consumptive water use. S Afr J Enol Vitic 1:7–14

Zyl JL van, Huyssteen L van (1988) Irrigation systems – their role in water requirements and the performance of grapevines. S Afr J Enol Vitic 9:3–8