

# Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy

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## Abstract

The relationships among water use and the crop coefficient of *Vitis vinifera* L. cv. Thompson Seedless with several measures of canopy development were determined with the aid of a weighing lysimeter in the San Joaquin Valley of California. At various times during two growing seasons, vine leaf area, calculated leaf area index (LAI) and the amount of shade cast on the ground directly beneath the canopy were determined. Leaf area was estimated by measuring the length of all shoots on the vines within the lysimeter and determining the relationship between length and leaf area per shoot and calculating total vine leaf area or by destructive harvests of vines of similar size surrounding the lysimeter. Shaded area was determined in 1998 using a grid (with 50 cm<sup>2</sup> individual sections) on the ground beneath the vine at solar noon and estimating the percent shade within each square. Total shade was calculated as the product of the area of all squares and the percent shade within each square. In 1999 shaded area was determined from an image of the shade beneath the canopy that was downloaded to a computer and the shade digitized with the use of a software program. Daily water use ranged from 4 to 60 L per vine across both years. Leaf area per vine ranged from 2 to 34 m<sup>2</sup> per vine during the study. The amount of shade cast on the ground was a linear function of total vine leaf area although there were differences between years. The north and south curtains of the vines' canopies were raised for a 2-week period in 1999 to simulate an overhead trellis system. The percent shaded area increased from 60 to 75% and vine water use increased from ~42 L per vine before the curtains were raised to greater than 60 L per vine after being raised. The crop coefficient ( $K_c$ ) increased from 0.9 to 1.3. Vine water use and the crop coefficient were linearly related to leaf area per vine, LAI and the amount of shade cast on the ground. However, the greatest  $R^2$  value (0.95) of the relationships with the  $K_c$  was that for shaded area compared to a  $R^2$  value of 0.87 for leaf area and LAI. The data indicate that due to the structure of a grapevine canopy the interception of light, as measured by the amount of shade cast on the ground, is a more important determinant of vine water use and the  $K_c$  than total leaf area or LAI.

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## 1. Introduction

The ability to estimate crop water use is important in agricultural areas such as California where the

production of crops are dependent upon the availability of irrigation water (Williams and Matthews, 1990). One means to calculate crop evapotranspiration ( $ET_c$ ) is with the use of crop coefficients ( $K_c$ ) and available evaporative demand data (reference evapotranspiration ( $ET$ ) or  $ET_o$ ) using the following equation:

$$ET_c = K_c \times ET_o \quad (1)$$

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The crop coefficient is dependent upon stage of crop growth, canopy height, cover and architecture (Allen et al., 1998). It has been demonstrated that the  $K_c$  is highly correlated with leaf area (Williams et al., 2003b), leaf area index (LAI) (de Medeiros et al., 2001; Ritchie and Johnson, 1990), canopy cover (de Medeiros et al., 2001; Heilman et al., 1982) and the fraction of light intercepted by the canopy (Ayars et al., 2003). The development of a simple method to estimate the seasonal  $K_c$  for different crops, including woody, perennial horticultural crops would be of great benefit to the agricultural industry.

Grapevines are the number one horticultural crop produced on a worldwide basis (Mullins et al., 1992). The many different trellis systems utilized to produce grapes are dependent upon the final grape product (wine, raisins or table (fresh) grapes) and the method of harvest, hand or machine. Row spacings in vineyards can vary from 1 m to greater than 3.7 m due to the size of equipment used or the type of trellis erected. Therefore, the amount of canopy cover within a single vineyard can be small or approach 100% due to the trellis and row spacing configuration. After full canopy has been achieved, the amount of canopy cover within California vineyards can range from less than 30% for a Vertical Shoot Positioned (VSP) trellis on a 3 m row spacing to greater than 90% for an overhead arbor type trellis system used for raisin and table grape production (Williams, unpublished data). The amount of canopy cover within vineyards of Central Spain (La Mancha region) have been reported to be approximately 10% due to the wide row and vine spacings (used to conserve water) and the small stature of vines (Jacobs et al., 1996). The above would indicate that the standard seasonal crop coefficients for grapevines that have been previously published (Allen et al., 1998; Doorenbos and Pruitt, 1977; Synder et al., 1989) and those recently developed (Williams et al., 2003a,b) would not be appropriate for all vineyard trellis and row width situations.

The grapevine canopy develops at some height above the ground due to the use of a trellis system making it easy to measure projected area beneath the canopy. A study to develop an irrigation schedule for grapevines grown in the San Joaquin Valley of California measured the amount of shade cast on the ground beneath the canopy at solar noon as a means of estimating canopy size (Peacock et al., 1987). Others have used the amount of shade cast on the ground to estimate water use of young compared to mature trees in orchards (Fereris, 1981; Goldhamer and Synder, 1989). It is assumed that water use of young trees is less than that of mature trees

until the amount of shade exceeds 61% of the area allocated per tree at which time  $ET_c$  is maximized. The ability to estimate or determine the amount of shade cast on the ground beneath grapevines and trees would be easier and less demanding than measuring the amount of light intercepted by those canopies as done by Ayars et al. (2003).

The present study was conducted to determine the relationship between canopy size, as measured by the amount of shade cast on the ground beneath grapevines growing in a weighing lysimeter, and vine water use. Other means of characterizing the grapevine canopy were also compared with that of shaded area. Previous reports using this lysimeter (Williams and Ayars, 2005; Williams et al., 2003b) and another one planted with peach trees at the same location (Ayars et al., 2003) have demonstrated that they are an accurate and reliable means of measuring evapotranspiration. The natural variation in the seasonal growth of the vines within the lysimeter across 2 years provided differences in the amount of shaded area measured as a function of vine leaf area. Another objective of this study was to determine how rapidly grapevine water use was affected by altering the orientation of the canopy while leaf area remained the same. Therefore, once full canopy had been achieved in 1999, the north and south curtains of both vines within the lysimeter were elevated to simulate an overhead arbor type of trellis system. After 2 weeks the curtains were lowered.

## 2. Materials and methods

The study was conducted at the University of California Kearney Agricultural Center (36°48'N, 119°30'W) where a weighing lysimeter had been installed in 1986 (Williams et al., 2003a). The lysimeter contained two *Vitis vinifera* L. (cv. Thompson Seedless, clone 2A) grapevines. The two vines were 2.15 m apart and 0.925 m from either end of the 4 m long lysimeter and 1 m from the sides. The trellis 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. The 1.4 ha vineyard surrounding the lysimeter was planted with vine and row spacings of 2.15 and 3.51 m, respectively. The length allocated to the two vine's canopies within the lysimeter was similar to that of the vines in the vineyard surrounding the lysimeter. 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. Row direction of the vineyard surrounding the lysimeter was approximately  $6^\circ$  south with respect to the east/west axis.

The vines in the lysimeter were irrigated with  $4 \text{ L h}^{-1}$  in-line drip emitters, spaced every 0.3 m. The drip tubing was attached to a wire suspended 0.4 m above the soil surface. The lysimeter's mass was recorded hourly to determine  $\text{ET}_c$  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  $\text{ET}_c$  over the  $8 \text{ m}^2$  lysimeter surface. When the threshold was exceeded, the lysimeter was irrigated. The number of irrigations per day ranged from 0 to 7 once irrigations commenced (Table 1) until the end of October each year.

The summation of hourly  $\text{ET}_o$  values was used with the summed hourly values of measured vine evapotranspiration ( $\text{ET}_c$ ) to calculate the daily crop coefficient ( $K_c$ ). The  $K_c$  was the ratio of  $\text{ET}_c/\text{ET}_o$ . Once irrigation commenced, the  $\text{ET}_c$  measured by the lysimeter was adjusted to an area equivalent loss of an individual vine in the lysimeter ( $4 \text{ m}^2$  of surface area), to that of vines in the surrounding vineyard ( $7.55 \text{ m}^2$  of surface area), by multiplying by 0.53. It was determined that soil water evaporation in the area outside the lysimeter was minimal (Williams and Ayars, 2005; Williams et al., 2003b). Further technical aspects of measuring vine water use ( $\text{ET}_c$ ) were similar to those previously given (Williams et al., 2003a,b).

Reference crop evapotranspiration ( $\text{ET}_o$ ) data were obtained from a California irrigation management information system (CIMIS) weather station (number 39) located 2 km from the vineyard site. Variables measured and calculations used to determine hourly and daily  $\text{ET}_o$  from CIMIS can be found in Synder and Pruitt (1992). Degree-day data were obtained from the University of California Statewide Integrated Pest Management Project's website. Degree-days were calculated using the sine method with a lower threshold of  $10^\circ\text{C}$ . Temperature data used in calculating degree-

days were obtained from the CIMIS weather station at the Kearney Agricultural Center.

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, California). 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. Field capacity of this soil type was approximately 22.0 vol.% ( $\theta_v$ ) while SWC at a soil moisture tension of  $-1.5 \text{ MPa}$  was approximately,  $8.0 \theta_v$  (Araujo et al., 1995).

Leaf area of vines within the lysimeter was estimated using non-destructive methods. At various times during the growing season 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, Inc., Lincoln NE). The relationship between shoot length and leaf area was determined via regression analysis on each day 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 measurements of shoots on the lysimeter-grown vines became too arduous the leaf area of vines ( $n = 3-4$ ) 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 irrigated with similar amounts of water growing elsewhere in the vineyard. Estimated leaf area of vines in the lysimeter was similar to leaf area measured on vines in the surrounding vineyard when such comparisons were made. Leaf area index of the two vines

Table 1

Dates of budbreak, initiation of irrigation within the lysimeter, anthesis, harvest and the accumulation of degree-days (base  $10^\circ\text{C}$ ) from March 15 to October 31 observed for the 2-year study

Year	Date of budbreak	Date of 1st irrigation	Date of anthesis	Date of harvest	Degree-day accumulation
1998	March 13 (72)	May 12 (132)	May 19 (139)	September 21 (264)	2363
1999	March 18 (77)	April 19 (109)	May 22 (142)	September 13 (256)	2405

Day of year is given in parentheses with each calendar date.

within the lysimeter was calculated by dividing estimated leaf area by the soil surface area allocated to each vine within the vineyard. The LAI on a projected (shaded) area was calculated by dividing estimated leaf area by measured shaded area.

Shaded area beneath the vines in the lysimeter during 1998 was determined by placing a grid (with 50 cm<sup>2</sup> individual sections) inscribed on a wooden board beneath the vines. The percentage of shade within each square was estimated in increments of 10%. The wooden grid was moved several times until all the shaded area beneath the vines had been determined. Total shade was calculated as the product of the area of all squares and the percent shade within each square. Shaded area in 1999 was determined by taking an image of the area beneath the vines with a digital camera (Sony Mavica FD-91; CCD resolution—850,000 pixels, image dimensions—1024 × 768, aperture setting—f2.4, shutter speed—1/60 s, file format—JPEG). The camera was held at a height of ~1.5 m or lower, depending upon the distance of the canopy from the soil surface, ~3 m from the lysimeter. A known rectangular area encompassing all the shade of each vine in the lysimeter, to be used as a reference area, was outlined with flagging tape attached to small wooden stakes driven into the soil. The image of the area beneath the canopy was downloaded to a computer and cropped to include only the outlined area. The reference area and shade within the reference area was digitized with Sigma Scan Pro Version 5 (Aspire Software International, Leesburg, VA). Since the images were only taken on cloudless days, there were sharp differences in color between the shade and that of the soil. The color image was converted to a gray scale and an intensity threshold was used to digitize the area of the entire image (reference area) and a new intensity threshold was used to digitize the area that was shaded. The amount of pixels comprising the shade was divided by those of the reference to obtain the fraction of shade within the known area. Once the shoots of the vines were within 0.45 m of the soil surface in 1999 it was not possible to use the digital camera to measure shade. A wooden grid (with ~230 cm<sup>2</sup> squares) was used thereafter and calculations done as described above. The shaded area determined with the wooden grid and the digital camera were compared several times during the 1999-growing season (early in the season) and were found to be within 3–6% of one another.

Shaded area was measured 30 min on either side of solar noon (12:30–13:30 h Pacific Daylight Time) each growing season. In 1999 the shaded area was measured using the digital camera early in the growing season to

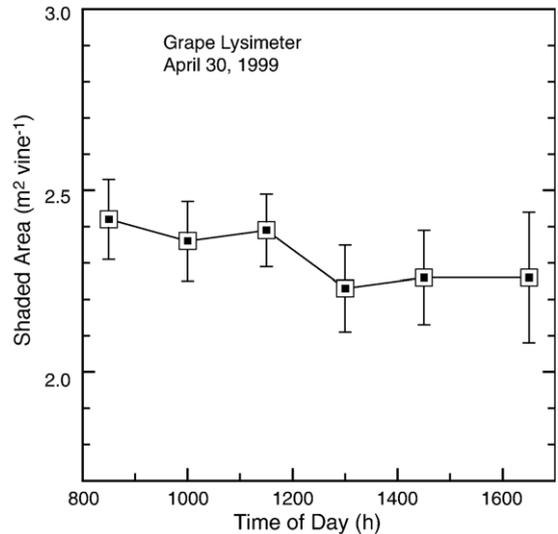


Fig. 1. The effects of time of day on the amount of shaded area cast on the ground beneath Thompson Seedless grapevine canopies on April 30, 1999. Each value represents the mean of five individual grapevines including the two vines in the lysimeter. Bars represent one standard deviation.

determine if the shade of the vines was affected by the position of the sun during the day (Fig. 1). Time of day had no significant effect on the amount of shade cast on the ground for vines planted to the row direction of the vineyard.

A wooden frame was constructed in 1999 in order to support the shoots of the north and south curtains of both vines so they could be raised. The arms (5 cm × 10 cm) of the frames were attached to the wooden end posts within the lysimeter slightly below the cross-arms and extended outward ~2.2 m from the trunks of the vines. The two arms were attached to one another with a 5 cm × 10 cm piece of wood at the end of the arms and another 1 m back toward the vines. A wire mesh was attached to the frame from its most outer point back toward the vines in order to support the ends of the shoots. The wire mesh extended from one end of the lysimeter to the other and was 1 m in width. The frames on either side of the vines were elevated using two 5 cm × 10 cm pieces of wood that extended from the frame to the soil surface of the lysimeter. Therefore, the frame was self-contained within the lysimeter to ensure that it was part of the lysimeter mass. Vine water use data were not used the days the frame was erected and dismantled.

Comparisons were made among vine water use and calculated crop coefficients and leaf area, leaf area index and the percent shaded area (shaded area divided by the area allocated to the vines within the vineyard;

Table 2

Rainfall, reference ET ( $ET_0$ ) and vine water use ( $ET_c$ ) for the grapevines growing in the weighing lysimeter measured from March 15 to October 31 for the 2 years of the study

Year	Monthly rainfall (mm)	$ET_0$ (mm)	$ET_c$ (L per vine)	$ET_c$ (mm)
1998	March—75; April—36; May—28; June—14	1075	5187	687
1999	March—11; April—33	1104	5923	784
			4763	631

Rainfall amounts (mm listed behind monthly abbreviations) are given when precipitation exceeded 5 mm for the month. Irrigation to the vines in the lysimeter was terminated on September 2, 1999. Vine water use amounts listed in the last two columns at the bottom represent  $ET_c$  from March 15 to September 1.

7.55 m<sup>2</sup>). Data were analyzed via regression analysis using CoHort Software.

### 3. Results

Budbreak occurred on March 13 and 18 while anthesis occurred on May 19 and 22 in 1998 and 1999, respectively (Table 1). The accumulation of degree-days between March 15 and October 31 were similar both years. Rainfall from March 15 through June amounted to 153 mm in 1998 but only 44 mm of rainfall occurred during the same time frame in 1999 (Table 2). Greater rainfall early on in 1998 is reflected in the mean soil water content measured at that time compared to 1999 (Fig. 2). There were technical difficulties with the irrigation system within the lysimeter during 1998 and the pump had to be turned on and off manually during portions of June and July. Despite this, SWCs were similar between the 2 years studied. Vine water use

amounted to 687 mm in 1998 between March 15 and October 31 and for the same period in 1999 amounted to 784 mm. The vines in the lysimeter were not irrigated for a period of 3 weeks beginning on September 2 in 1999. Water use in 1999 between March 15 and September 1 was equivalent to 631 mm (Table 2).

The amount of shade cast on the ground and leaf area per vine was measured on nine different dates in 1998 (Table 3). Leaf area ranged from 2 to 25 m<sup>2</sup> per vine in 1998 and that of shaded area ranged from 0.82 to 4.76 m<sup>2</sup> per vine. The highest  $ET_c$  on the 9 days leaf area and shaded area were measured was 6.99 mm. The lowest and highest values of  $ET_0$  were 4.63 and 7.01 mm per day. On August 10, 4.2 m<sup>2</sup> of leaf area per vine was removed when the vines in the lysimeter were hedged. The last date that shaded area was measured occurred on August 17 in 1998.

Water use during the 1999-growing season increased almost linearly from March 15 until approximately 750 DDs later (Fig. 3). The week before the canopy curtains were raised vine water use averaged 42 L per day and at this time measured leaf area and shaded area were 34.0 and 4.23 m<sup>2</sup> per vine, respectively. Once the curtains were raised shaded area increased to 5.71 m<sup>2</sup> per vine and vine water use increased to greater than 60 L per day. Vine water use after the curtains were lowered was similar to that measured prior to the curtains being raised. Shortly thereafter, the shoots of the vines in the lysimeter were hedged removing almost 10 m<sup>2</sup> of leaf area per vine. The last date in which shaded area was measured in 1999 was August 17, 1521 DDs after March 15. The irrigation pump to the lysimeter was turned off on September 2 that year and no further measurements were taken.

The  $K_c$  increased in 1999 to a maximum of 0.9 approximately 800 degree-days after March 15 (Fig. 4). When both foliage curtains of the vines were raised, the  $K_c$  increased to a value of almost 1.3. Two weeks later the foliage curtains were lowered and the  $K_c$  decreased to 0.95. Subsequently, the shoots of the vines were hedged on July 21 (1170 DDs after March 15) and the

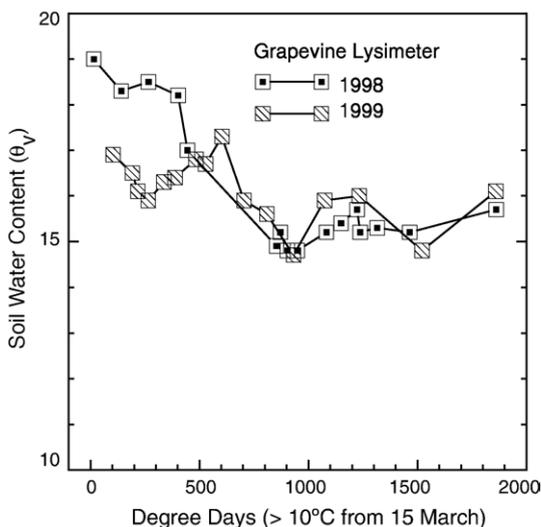


Fig. 2. Mean soil water content (expressed as percent by volume:  $\theta_v$ ) measured in the weighing lysimeter during the 1998 and 1999-growing seasons. An individual data point is the average of two access tubes measured at six depths (from 0.23 to 1.65 m below the soil surface).

Table 3

Leaf area, shaded area, vine water use ( $ET_c$ ) and reference ET ( $ET_o$ ) on various dates during the 1998-growing season

Calendar date	Day of year	Degree-days	Leaf area ( $m^2$ per vine)	Shaded area ( $m^2$ per vine)	$ET_c$ (mm)	$ET_o$ (mm)
April 20	110	141	2.0	0.82	0.54	4.63
May 1	121	241	5.9	1.31	1.12	5.26
June 1	152	435	15.4	2.71	2.83	5.54
July 6	187	837	19.5	3.45	4.32	6.97
July 20	201	1082	22.0	3.85	5.85	7.01
July 28	209	1223	24.9	4.62	6.12	6.27
August 4	216	1337	25.3	4.76	6.99	6.37
August 10	222	1446	21.1	3.83	6.17	6.13
August 17	229	1576	21.6	3.65	5.82	6.19

On August 9 approximately  $4.2 m^2$  of leaf area was removed from each vine in the lysimeter when the shoots of the vines were hedged (simulating what had been done mechanically for the vines in the surrounding vineyard). Vine water use is based upon an area of  $7.55 m^2$  soil surface area per vine.

$K_c$  decreased to 0.8 and then slowly increased thereafter to a value of 1.0 prior to the irrigation pump being turned off. At this time leaf area and shaded area per vine were  $25.1$  and  $3.55 m^2$ , respectively.

Shaded area of the vines increased almost linearly from budbreak until 750 degree-days after March 15 (Fig. 5). Subsequently, the amounts of shade varied due to shoot hedging and shoot re-growth. There was a linear relationship between shaded area and estimated leaf area of the vines in the lysimeter (Fig. 6).

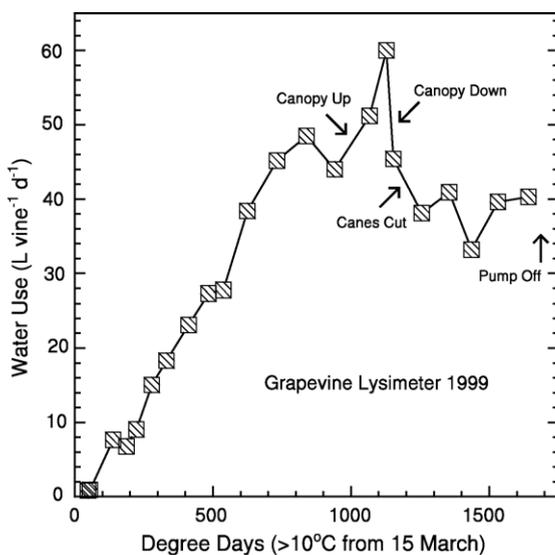


Fig. 3. Daily water use of Thompson Seedless grapevines measured from March 15 until the irrigation pump to the lysimeter was turned off on September 2 (1746 DDs after March 15) in 1999. Each data point is the average daily value for a 7-day period. The arrows represent the approximate days when the north and south portions of the canopy were raised or lowered and when the apical portions of the shoots were hedged (canes cut), approximately 0.45 m above the soil surface.

Differences between the 2 years in the amount of shade as a function of leaf area occurred when leaf area exceeded  $20 m^2$  per vine. There were no visual differences in the shape of the canopies observed by the senior author at that time.

When the LAI is expressed on a projected (shaded) area per vine basis instead of land area per vine basis for all but the first two measurement dates in 1998, at DDs greater than 400 (Table 3), the LAI remained constant at a value of  $5.60 m^2 m^{-2}$  ( $\pm 0.08$  [S.E.]). Using the last nine measurement dates in 1999, at DDs greater than 400, the mean LAI per shaded area basis was  $7.06$  ( $\pm 0.2$ ).

Grapevine water use was a linear function of percent shaded area (Fig. 7). Water use (expressed as mm per

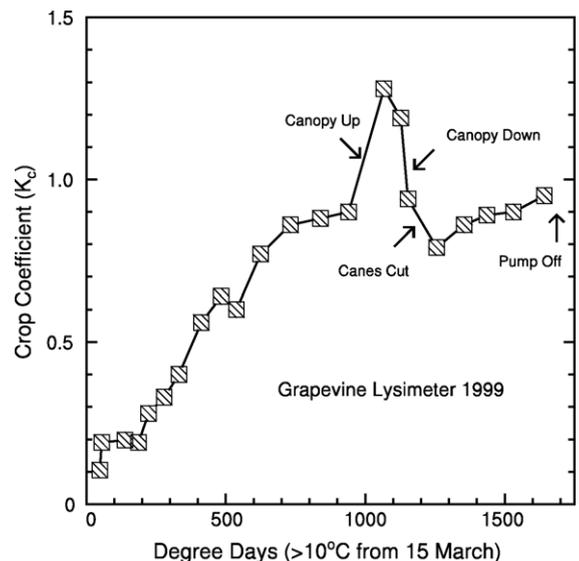


Fig. 4. The seasonal progression of the crop coefficient ( $K_c$ ) calculated for Thompson Seedless grapevines during 1999. Other information is as given in Fig. 3.

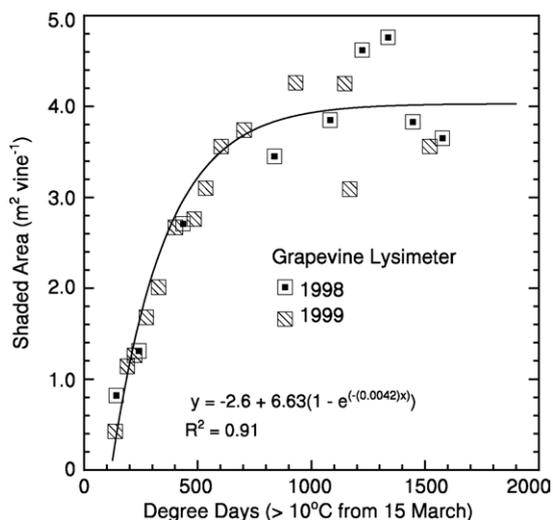


Fig. 5. Shaded area measured beneath the two Thompson Seedless grapevines grown in the weighing lysimeter in 1998 and 1999 as a function of degree-days (DDs) after March 15. The shaded area of the vines when their canopy curtains were raised in 1999 is not included in the figure.

day) was also linearly related with leaf area ( $y = 0.366 + 0.209x$ ;  $R^2 = 0.89$ ) and LAI ( $y = 0.369 + 1.587x$ ;  $R^2 = 0.89$ ). The  $K_c$  was a linear function of leaf area per vine (Fig. 8), LAI (Fig. 9) and the percent shaded

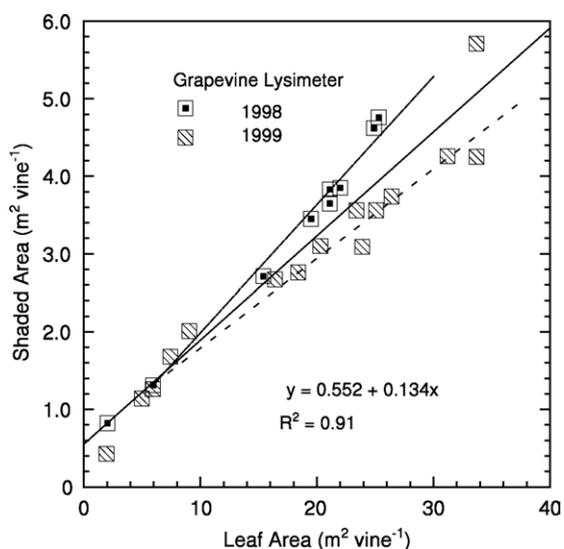


Fig. 6. The relationship between shaded areas cast on the ground beneath the Thompson Seedless grapevines in the lysimeter and their estimated leaf areas. The solid line represents a linear regression using data points from both years. The upper line represents a linear regression using the data points from 1998 ( $y = 0.336 + 0.165x$ ;  $R^2 = 0.99$ ). The lower dashed line represents a linear regression using the data points from 1999, except when the curtains were raised ( $y = 0.636 + 0.115x$ ;  $R^2 = 0.97$ ).

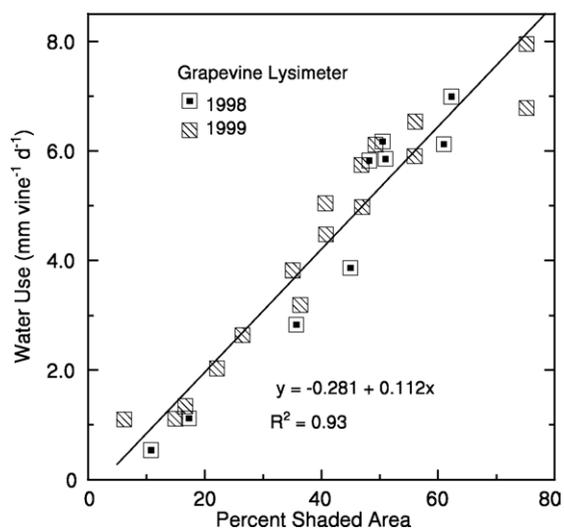


Fig. 7. Thompson Seedless grapevine water use as a function of the percent shaded area measured beneath the canopies of the two vines growing in the lysimeter. Percent shaded area was calculated by dividing the shaded area by the area allotted per vine in the vineyard surrounding the lysimeter ( $7.55 \text{ m}^2$ ) and then multiplying by 100. Each data point represents the amount of water used by the vines on the day-shaded area was measured. To convert from mm per vine to liters per vine multiply by 7.55.

area (Fig. 10). The coefficient of determination for the relationship between the percent shaded area and the  $K_c$  was greater than those for leaf area per vine or LAI.

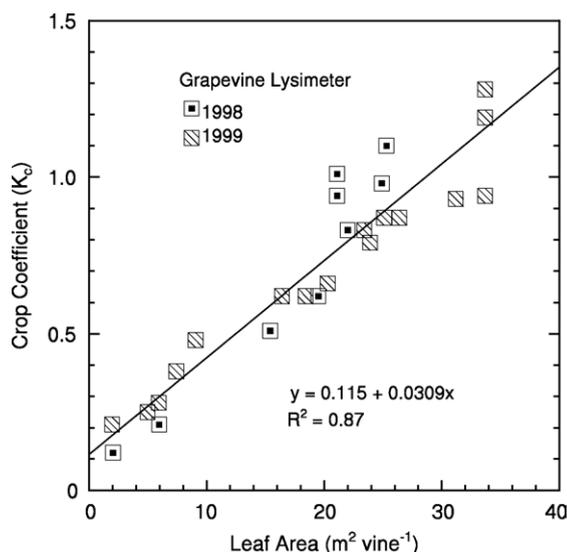


Fig. 8. The relationship between the calculated crop coefficient ( $K_c$ ) and the estimated leaf area per vine of Thompson Seedless grapevines growing in the lysimeter during 1998 and 1999. The  $K_c$  data was calculated by dividing grapevine  $ET_c$  (mm per day) by reference  $ET$  ( $ET_0$ ) on the day the leaf area was determined.

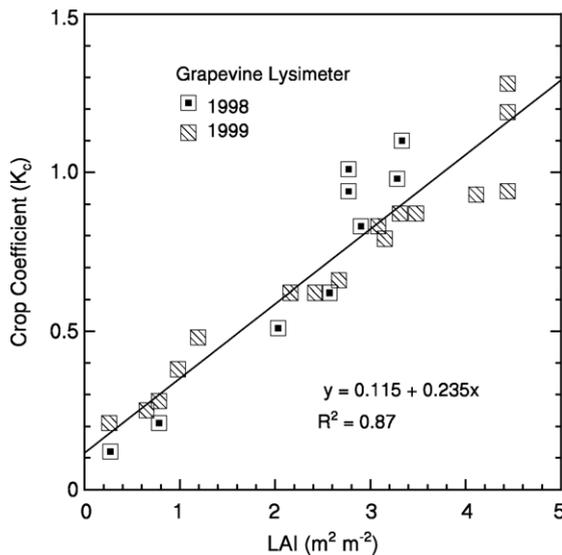


Fig. 9. The relationship between the calculated crop coefficient ( $K_c$ ) and the estimated leaf area index (LAI) of Thompson Seedless grapevines growing in the lysimeter determined during 1998 and 1999. The LAI was determined by dividing the leaf area by  $7.55 \text{ m}^2$ , the area allotted per vine in the vineyard surrounding the lysimeter. Other information is as given in Fig. 7.

#### 4. Discussion

The use of crop coefficients in estimating  $ET_c$  (see Eq. (1)) is widely accepted (Allen et al., 1998). The  $K_c$  is dependent upon crop type and management

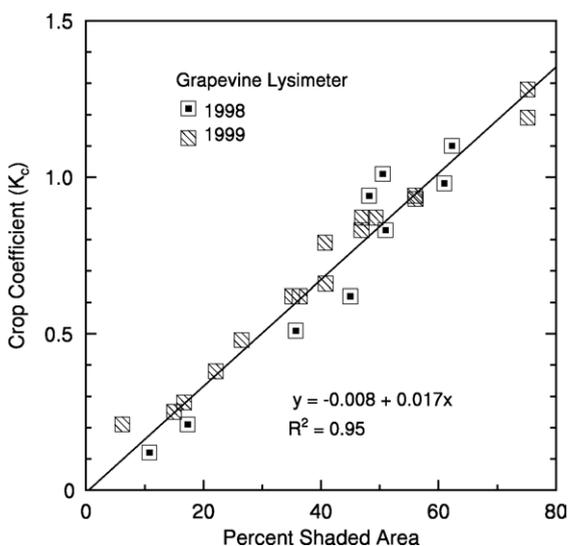


Fig. 10. The crop coefficient ( $K_c$ ) of Thompson Seedless grapevines growing in the weighing lysimeter as a function of the percent shaded area measured beneath the two vines. The  $K_c$  was calculated by dividing grapevine  $ET_c$  (mm per day, from Fig. 7) by reference  $ET_c$  ( $ET_0$ ) on the day the shaded area was measured.

practices, which will influence the rate of canopy development and the ultimate canopy size, i.e. amount of ground cover (Allen et al., 1998; Hatfield, 1990). Several authors have related the  $K_c$  to various measures of crop development such as leaf area (Williams et al., 2003b), LAI and percent ground cover (Al-Kaisi et al., 1989; de Medeiros et al., 2001; Heilman et al., 1982; Ritchie and Johnson, 1990) and in most cases they were linearly related for different crops. It was recently demonstrated that the  $K_c$  of peach trees (*Prunus persica* (L.) Batsch) was a linear function of the fraction of light intercepted by the canopy at midday (Ayars et al., 2003).

In the present study it was demonstrated that vine water use and the  $K_c$  were linearly correlated with all measures of canopy development used to characterize Thompson Seedless grapevines. The linear relationship between the  $K_c$  and vine leaf area was similar to that previously measured on the same vines (Williams et al., 2003b). However, the coefficient of determination between the  $K_c$  and leaf area was less than that for the relationship between the  $K_c$  and percent shaded area. In addition, the increase in water use and the  $K_c$  when the canopy's curtains were raised in 1999, without a concomitant increase in the amount of leaf area per vine, indicates that it is the amount of leaf area exposed to direct sunlight (also referred to by others as effective or exposed leaf area) and not the total amount of leaf per vine that determines water use of a grapevine.

There are several studies on grapevines demonstrating that the amount of light intercepted by the vine's canopy is important in determining whole vine water use under non-water limiting conditions. Riou et al. (1994) concluded that the ratio between vine canopy transpiration and  $E_p$  (Penman Potential ET) almost equalled the ratio of the amount of light intercepted by the vines' canopy and that intercepted by the whole vineyard. Trambouze and Voltz (2001) used this ratio in modeling the transpiration of a vineyard and they found that when the canopy was larger, due to natural variation in canopy size from one season to the next, light interception increased and vine water use was greater. Heilman et al. (1996) found that trellis type influenced canopy latent heat flux. Water use was greater when the canopy was allowed to grow unrestrained (open hedgerow) compared to when the canopy was restricted (compact hedgerow). In fact, canopy latent heat flux per unit leaf area was greater for the open hedgerow versus the compact hedgerow vines (Heilman et al., 1996). Therefore, the amount of shade measured on the ground beneath the grapevines within the lysimeter in this study provided an indirect measure of the amount of sunlight intercepted by

the canopy, the amount of water the vine used and the resultant  $K_c$ .

The slope of the relationship between the  $K_c$  and the percent shaded area in this study was 0.017 with an intercept close to zero. The relationship between the  $K_c$  and the proportion of midday light interception (expressed as a fraction) by peach trees resulted in a slope of 1.59 (Ayars et al., 2003). If the proportion of midday light interception were converted to a percent shaded area value the resultant slope would be 0.0159, similar to that found in this study. When comparing the relationship between the  $K_c$  and percent shaded area generated in this study for grapevines and that between the basal  $K_c$  and percent ground cover of beans (*Phaseolus vulgaris* L.) reported by de Medeiros et al. (2001) the data overlap at ground cover (shaded area) values between 20 and 70%. Heilman et al. (1982) reported that the relationship between the crop coefficient and percent cover of alfalfa resulted in a slope of 0.012. Lastly, if the basal projected areas of Colomard grapevines grown in Australia (Stevens and Harvey, 1996) were converted to percent shaded area and the ratio of  $\Delta S_{ET}/ET_o$  ( $\Delta S_{ET}$  = soil water depletion by grapevine evapotranspiration  $\approx$  vineyard  $ET_c$ ) were used as the  $K_c$  the relationship between the two would result in a slope of 0.018, similar to the  $K_c$  versus shaded area relationship from this study. However, the intercept (0.12) would be greater than the 0.008 reported in this study. It would appear that the linear relationship between percent shaded (or ground cover) area and the  $K_c$  may be a universal phenomenon and that slight differences among studies regarding the slopes and intercepts of this relationship could be due to the methods by which  $ET_c$  and shaded areas were determined and the cultural practices (particularly irrigation amounts and frequencies) being used to grow the crop.

The lack of a technique for estimating leaf area of a crop was at one time thought to be a major problem associated with water balance and other hydrological methods of irrigation scheduling (Kanemasu et al., 1983). The development of indirect methods for LAI determinations (Grantz and Williams, 1993; Jonckeeere et al., 2004) or optical LAI measurements by means of hemispherical photography (Jonckeeere et al., 2004) may assist in overcoming this obstacle. However, results from this study indicated that shaded area cast on the ground and not grapevine leaf area and/or LAI was the best predictor of grapevine water use and the  $K_c$ . Therefore, a digital camera (and the appropriate software to digitize the amount of shade) would be the only hardware required to follow the seasonal

development of the grapevine canopy under most circumstances.

A LAI of 3.0 has been used as an estimate of when full cover occurs (Allen et al., 1998) and also when  $ET_c$  (Tanner and Jury, 1976) or  $K_c$  will be maximized for a given crop (Ritchie and Johnson, 1990; Al-Kaisi et al., 1989). The amount of ground cover required to maximize  $ET_c$  has been reported to range from 50 to 80% for various annual crops (Tanner and Jury, 1976). It also is assumed that water use of trees is maximized once the shade on the ground reaches 61% with no further increase in  $ET_c$  above that value (Feres, 1981; Goldhamer and Synder, 1989). In this study there was a linear increase in both water use and the  $K_c$  as the LAI increased up to a maximum of  $\sim 4.5$ . The  $K_c$  at a LAI of 3.0 was 0.82. The greatest percent shaded area measured in this study without altering the canopy was 60% and the  $K_c$  was  $\sim 1.0$  at that value. This is similar to that reported previously for these same vines (Williams et al., 2003b; Williams and Ayars, 2005) but greater than the  $K_c$  of 0.7 estimated for crops with a ground cover between 40 and 60% (Allen et al., 1998). When the curtains of the vines were raised, shaded area increased up to 75% and the  $K_c$  increased to 1.27. The data presented here and that from Ayars et al., (2003) would indicate that the  $K_c$  and water use of vines and trees may continue to increase even when the LAI and percent shaded area increases above values which in the past have been assumed to maximize both. Greater canopy height and roughness in vineyards and orchards may account for  $K_c$ s greater than 1.0 (Allen et al., 1998; Feres and Goldhamer, 1990).

Wright (1985) suggested that it would be better to have a means of relating crop coefficients more directly to crop development (or the development of crop cover) than for example, day of year or days after planting. This would also apply to grapevines in California where date of budbreak can vary considerably due to location, cultivar and cultural practices. It was previously shown that the development of leaf area on Thompson Seedless grapevines under non-limiting soil moisture conditions (Williams, 1987; Williams et al., 2003b) and the  $K_c$  (Williams et al., 2003b) were highly correlated to degree-days (base temperature  $10^\circ\text{C}$ ). The seasonal development of shaded area under the vines in this study was also highly correlated with degree-days. It has been shown that the amounts of shaded area measured beneath a particular trellis system (such as for example, a 'Lyre' trellis) at four diverse locations in California throughout the growing season were similar to one another when expressed as a function of degree-days (Williams, unpublished data).

This was independent of cultivar, rootstock and row direction. Therefore, shaded area could be used as a measure of grapevine canopy development and the relationship between shaded area and the  $K_c$  (Fig. 10) could then be used to estimate the  $K_c$ . Thereafter, the  $K_c$  could be calculated solely as a function of degree-days. This procedure has been used successfully by the senior author in vineyards throughout California to schedule water applications in various irrigation studies.

## 5. Conclusions

Grapevine water use and the calculated  $K_c$  were highly correlated with all measures of Thompson Seedless canopy development. However, the best fit of the  $K_c$  with the different measures of canopy development was its relationship with percent shaded area. The slope of the linear relationship between the  $K_c$  and percent shaded area found here was similar to several other studies in which the relationship was presented or recalculated herein. It was proposed more than 20 years ago that the  $K_c$  could be estimated using remote sensing based upon the premise that the  $K_c$  was a linear function of groundcover (Heilman et al., 1982). Results from this and several other studies (cited previously) using both horticultural and agronomic crops would indicate that this technique certainly deserves further research.

Differences in trellis types and row spacing, both of which could affect the fraction or percent ground cover, are not presently accounted for in current publications listing crop coefficients for vineyards. The expression of the  $K_c$  as a function of percent shaded area as given in this paper could account for differences in water use requirements for vineyards having the same trellis system but different row spacings or vineyards having the same row spacing but different trellis systems. For example, a Vertical Shoot Position trellis for two different vineyards with row spacings of 1.5 and 2.5 m may have the same amount of shaded area per vine (assuming similar vine spacings) but the percent shaded area and therefore the calculated  $K_c$ , would be greater at the narrower row spacing. Therefore, water use per unit land area for a vineyard with narrower row spacings would be greater than one with wider rows. From a practical standpoint, managers could estimate their own individual vineyard  $K_c$  by simply measuring the width of the shade cast upon the ground and using the relationship between percent shaded area and the  $K_c$  from that given in this paper providing estimates of grapevine water use at 100% of  $ET_c$ .

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