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SYNOPSIS: How much irrigation water is required to grow quality winegrapes depends upon site, the stage of vine growth, row spacing, size of the vine's canopy, and amount of rainfall occurring during the growing season. Below, growers are presented with means to determine when irrigations should commence and to calculate full vine water use based on the results of 10 years of field trials in California winegrape growing regions. Implications for such information to assist in vineyard irrigation management are included.

Coastal, winegrape production areas in California are characterized by warm days and cool nights, although high temperatures (104† to 116†F) may occur for a few days each growing season. Some areas may have fog lasting late into the morning.

Rainfall is greater in northern coastal valleys and diminishes as one travels south. In coastal valleys, evaporative demand can range from 35 to 50 inches of water throughout the growing season (between budbreak and the end of October).

Many of the soils in the coastal production areas are clay loam to clay-type soils, which at field capacity, generally hold more water than sandy-type soils. Since the majority of rainfall occurs during the dormant portion of the growing season in these areas and vineyard water use can be greater than the soil's water reservoir after the winter rainfall, supplemental irrigation of vineyards may be required at some point during summer months.

IRRIGATION MANAGEMENT

No matter where grapevines are grown, two major questions concerning vineyard irrigation management must be answered:
1) When to start? and 2) How much water to apply?

When to start irrigating

Deciding when to begin irrigating can be determined several ways. Soil-based tools such as a neutron probe and capacitance sensors can determine the actual or relative amounts of water in the rooting zone of grapevines. Plant-based tools, such as a pressure chamber, can be used to measure vine water status.

Regardless of the method, a "value" is determined which indicates that the vines may need water. Once this value is reached, an irrigation event should occur.

Using a pressure chamber

Water has free energy, a capacity to do work. In plants, water's free energy (or chemical potential) is usually referred to as "water potential." Pure water will have a water potential of 0 bars (bar is the unit of measurement).

Any solute (such as sugars, mineral ions, and amino acids) added to water will lower its water potential, i.e. the water potential will become more negative. The same can be said of a plant's water potential.

For example, when more water is lost from a leaf via transpiration than moves into the leaf from the vascular tissue, its water potential will become more negative due to a relative increase in its solute concentration. This is important as water in plants and soils moves from regions where water potential is relatively high to regions where water potential is relatively low. Such differences in water potential will result in movement of water from cell to cell within a plant or from regions within the soil profile that contain more moisture to those with less.

One way to measure the water potential of a plant organ in the field (such as a leaf) is by using a pressure chamber.

The leaf's petiole is cut and the leaf quickly placed into the chamber with the cut end of the petiole protruding out of the chamber. Once the leaf is removed from the plant, the tension in the petiole's xylem is released and the sap withdraws from the cut surface and moves into the blade.

Randell Johnson (Hess Collection Winery, Napa, CA) uses pressure chamber. (Photos by Richard Camera.)

As the chamber is pressurized, the water potential of the leaf is raised by the amount of pressure applied so that at the **balance pressure** (the pressure required to force the sap to the surface of the cut end of the petiole), the water potential is zero. The original leaf water potential plus the balance pressure equals zero. Therefore, the **negative** of the balance pressure equals the original leaf water potential.

A more complete explanation of the pressure chamber technique, theory, possible errors, and problems can be found in "Measurements of plant water status," Hsiao.[2]

The water potential of a plant leaf will be greatest at pre-dawn, then decline (become more negative) during the day to reach a daily minimum, then increase as the sun sets. This type of pattern will occur regardless of the availability of water in the soil profile.

However, pre-dawn and midday minimum values will be more negative for plants experiencing soil moisture deficits than those given greater amounts of water.[7] Thus, leaf water potential can be used to estimate the water status of a plant. Units of water potential are expressed in bars, as mentioned above, or megapascals (MPa) (1.0 MPa = 10 bars).

In all of my irrigation trials, I have measured leaf water potential to assess vine water status. I usually measure midday leaf water potential between 12:30 and 1:30 pm. I select mature, fully expanded leaves exposed to direct sunlight (no shading on the leaf). I have found that any fully expanded leaf on the outside of the canopy will be appropriate as long as it is not senescent (starting to turn yellow), diseased, or suffering from insect damage.

The leaf blade is enclosed inside a plastic bag (plastic sandwich bags are satisfactory) and then the petiole is cut with a **sharp** razor blade. The plastic bag enclosing the leaf blade is to minimize transpiration between petiole excision and pressurization within the chamber. I have found a difference in leaf water potential of 2 to 3 bars between bagged grape leaves and those that were not bagged (the latter being more negative).

The bagged leaf is placed inside the chamber with the petiole sticking out (see photo). The time from enclosing the leaf inside the plastic bag to placing it inside the chamber should be 10 seconds or less. The chamber is pressurized with compressed nitrogen until the sap **just** exudes from the cut end of the petiole. If the sap forms into a lens or hemisphere, then the sample has been over-pressurized.

The petiole should be carefully observed in order to capture the measurement when the sap just exudes from the cut end.

The recommended rate of pressurization is less than 1 bar per second initially, then slowed to less than 0.2 bar per second as the balancing pressure is approached.[2] The end point should be observed with a magnifying lens and adequate light.

While the above description of the pressure chamber involves use of compressed nitrogen, a new chamber has been developed that doesn’t require compressed gas cylinders. This chamber is pressurized via a manual pump and is very portable.

Water potential values obtained by using this technique can be dependent upon ambient vapor pressure deficit (VPD), which increases as relative humidity decreases; temperature and light, because all of these contribute to evaporative demand; time of day the measurement is made; and the amount of water in the soil profile.

Since, time of day is very important, and the evaporative demand will vary considerably throughout the day, I limit taking leaf water potential measurements to one-half hour on either side of solar noon. That is when a grapevine uses the greatest amount of water on a daily basis.[6]

I have found that midday leaf water potential values of fully irrigated vines on a day of low evaporative demand (ambient temperature at the time of measurement 85†F) will be approximately 1 bar higher (less negative) than on a day when ambient temperature is 98†F at the time of measurement. This is also true for vines that are deficit-irrigated.

Table I — Crop coefficients for a VSP trellis as a function of degree-days (DDs) from budbreak and row spacing. Degree-days (DDs) are expressed in Centigrade (C) and Fahrenheit (F). Base temperatures used in calculating DDs are 10°C and 50°F.

DDs (C)	DDs (F)	k_c 6 ft*	k_c 7 ft	k_c 8 ft	k_c 9 ft	k_c 10 ft
100	180	0.17	0.15	0.13	0.12	0.10
200	360	0.22	0.19	0.17	0.15	0.13
300	540	0.28	0.24	0.21	0.19	0.17
400	720	0.35	0.30	0.26	0.23	0.21
500	900	0.42	0.36	0.31	0.28	0.25
600	1080	0.49	0.42	0.37	0.33	0.29
700	1260	0.56	0.48	0.42	0.37	0.33
800	1440	0.62	0.53	0.46	0.41	0.37
900	1620	0.67	0.58	0.51	0.45	0.40
1000	1800	0.72	0.62	0.54	0.48	0.43
1100	1980	0.76	0.65	0.57	0.50	0.45
1200	2160	0.79	0.67	0.59	0.52	0.47
1300	2340	0.81	0.69	0.61	0.54	0.48
1400	2520	0.82	0.71	0.62	0.55	0.49
1500	2700	0.82	0.71	0.62	0.55	0.49

*The equation used to calculate kcs for the 6-foot row was:

$$k_c = 0.87/(1 + e^{(-((x-525)/301))})$$

where x is degree-days in centigrade.

Table II — The effect of trellis type and row spacing on estimated vine water use of grapevines assuming an ET_0 of 1.5 inches for the time frame used. HD stands for a high density planting, 1 m x 1 m, using a smaller version of a VSP trellis.

Trellis Type	Row Spacing	ET_o (inches)	k_c	ET_c (inches)	ET_c (gal/acre)	ET_c (gal/vine)
VSP	6 ft.	1.5	0.81	1.22	33,550	27.8
VSP	9 ft.	1.5	0.54	0.81	22,275	27.6
Lyre	9 ft.	1.5	0.83	1.25	34,375	42.5
HD	1 m	1.5	0.91	1.37	37,675	9.3
GDC	12 ft.	1.5	0.75	1.13	31,075	51.4

Assumptions: Vine spacing for all trellises is 6 ft., except in the HD vineyard. Therefore vine density is 1,208, 808, 808, 604, and 4,049 vines per acre for the VSP 6 ft. row, VSP 9 ft. row, Lyre, and GDC trellis and HD planting, respectively. The k_cs used for the VSP 6 and 9 ft. rows is from DDs (C) 1300 row in Table I. Other k_cs used are from L.E. Williams, unpublished data. ET_c in inches was obtained by multiplying ET_o by the k_c. It was assumed that there is 27,500 gallons per acre-inch of water.

One can also assess vine water status by taking water potential readings prior to sunrise (pre-dawn leaf water potential) or by measuring stem water potential at midday.

Stem water potential is determined by enclosing a leaf in a plastic bag surrounded by aluminum foil, at least 90 minutes prior to when readings are to be made. This procedure eliminates transpiration and the leaf water potential will come into equilibrium with the water potential of the stem (i.e. stem water potential).

A recent study on almond trees has shown that water potential values measured on shaded leaves (covered with a damp cloth just before leaf excision) are very similar to values of stem water potential.[1]

I have compared leaf water potential of leaves under naturally occurring shade with stem water potential values of grapevines this past summer and found the two are very similar in some instances. In other instances they were not.

I believe the discrepancy is due to the fact that on some trellis systems (such as the VSP), it is difficult to find leaves that are completely shaded (no sunflecks present on individual leaves) or in deep enough shade that transpiration truly is minimal.
Some researchers feel that stem water potential is a better measure of vine water status than leaf water potential since it somewhat minimizes the effects of the environment on an exposed leaf as outlined above.

However, Dr. Merilark Padgett-Johnson and I have demonstrated (unpublished data) that pre-dawn leaf, midday leaf, and midday stem water potential of Vitis vinifera cultivars and different Vitis spp. are all highly correlated with one another and with other measures of vine water status. Based on these findings, midday leaf water potential is an appropriate and convenient means of estimating vine water status, however, one must follow precisely the techniques outlined above.

It is interesting to note that D.A. Goldhamer and E. Fereres found that a major source of variation in determining tree water status (stem and shaded leaf water potential) is due to operator error.1 Thus, whoever is taking your vine water status measurements, whether midday leaf or stem water potentials, should be cognizant of possible errors associated with their technique.

My research indicates that the midday leaf water potential of vines that are irrigated at 100% of water use is generally never more negative than –10 bars (equivalent to a stem water potential value of –7.5 bars).[7] Measurements are made one-half hour on either side of solar noon, that is 1 pm PDT.

In my current irrigation experiments, I generally do not initiate the application of water until midday leaf water potential is at or more negative than –10 bars.

At present, many growers and vineyard consultants do not begin irrigation of white wine cultivars until a midday leaf water potential value of –10 bars has been reached or a –12 bar value for red wine cultivars. The date during the growing season these values are obtained is dependent upon rooting depth of the vines, soil texture, soil moisture content, vine canopy size, row spacing, trellis type, and evaporative demand.

For example, in 2001, leaf water potential of Thompson Seedless grapevines at the Kearney Ag Center did not reach –10 bars until bloom (the first week of May), at which time irrigations began.

In a Cabernet Sauvignon trial near Oakville in 2001, irrigation was not initiated in a trellis and irrigation study until a midday leaf water potential value of –11 bars was measured. Accordingly, irrigation was initiated on June 3, June 11, and July 10 for a VSP trellis (1m X 1m planting), a Wye (or lyre) trellis with 9-ft. row spacing, and a VSP trellis with 9-ft. row spacing, respectively.

Since soil type and rooting depth were the same for all trellises in the trial near Oakville, the differences in the date irrigations began (i.e. when leaf water potential reached –11.0 bars at midday) were due to the differing amounts of water used by each. Hence the rate water was depleted from the soil profile.

How much water to apply

I have spent the last 10 years determining irrigation requirements for raisin, table grape, and wine grape vineyards in all major grape-growing regions of California.

Regardless of grape type, in my opinion, once the decision to begin irrigations is made, vine water requirements are dependent upon evaporative demand at the location of the vineyard, stage of vine development, and percent ground cover by the vine’s canopy. This is because the amount of water depleted from the soil profile has been significantly reduced by that time (especially if no water had been applied from the time of budbreak to that point) and the majority of the water a vine subsequently will use is dependent upon what is applied.

The information needed to schedule irrigations at daily, weekly, or other intervals throughout the growing season includes potential evapotranspiration (ET_o) and reliable crop coefficients (k_c). Potential ET (also known as reference ET) is the water used per unit time by a short green crop completely shading the ground. Ideally, the crop is of uniform height and never water-stressed.

Potential ET (ET_o)

ET_o is a measure of the evaporative demand of a particular geographic region throughout the year. Current (or near-real time) ET_o data are available from the California Irrigation Management Information System (CIMIS) which is operated by the California Department of Water Resources.

There are more than 90 weather stations located around the state where environmental data are collected to calculate ET_o.
Environmental variables measured to calculate ET_o are mean, hourly solar radiation, air temperature, vapor pressure, and wind speed. These variables are then used to calculate other variables such as net radiation and vapor pressure deficit which are then inserted into an equation to calculate ET_o.[4]

Potential ET may also be obtained from weather stations operated by other entities (such as stations operated by the Paso Robles Vintners & Growers Association in the Paso Robles region).

Potential ET will vary seasonally and is low at the beginning of the season, highest in mid-summer, and then decreasing thereafter. Between budbreak and the end of October, ET_o can range from 35 to 50 inches of water in the coastal valleys of California.

For example, ET_o from March through October in 1997 for the Carneros region of Napa Valley, Greenfield in the Salinas Valley, Paso Robles, and Fresno were 44, 44, 51, and 48 inches, respectively.

Historical ET_o in the Santa Maria region for the above-mentioned months is estimated to be 36 inches. Therefore, if identical vineyards (same cultivar, trellis system, row spacing, canopy size, etc.) were growing at all five locations, then seasonal vine water use would be lowest in Santa Maria and highest in Paso Robles. The differences would be due to varying evaporative demand at those locations.

Crop coefficients

The next piece of information needed to determine vineyard water use is seasonal crop coefficients (k_c). The k_c is the fraction of water a non- water-stressed crop uses in relation to that of ET_o:
$k_c = ET_c \div$ by ET_o
where ET_c is crop ET. The k_c is dependent upon the stage of vine growth, degree of ground cover (shading), height, and canopy resistance (regulation by the vine or crop). The kc will vary throughout the growing season; it is not a constant fraction of ET_o. It is low early on and then as the canopy develops, it will increase (Table I).

In the past, seasonal crop coefficients have been developed for vineyards in the San Joaquin Valley. Unfortunately, when these seasonal crop coefficients were utilized in coastal valley vineyards, they did not work very well.

Various means of adapting these crop coefficients to different trellises and row spacings have included the use of another coefficient (canopy coefficient) that is a function of canopy size.

In order to develop crop coefficients, one must be able to measure or estimate grapevine water use throughout the growing season. With the aid of a weighing lysimeter, I have determined seasonal crop coefficients for Thompson Seedless grapevines grown at the University of California's Kearney Agricultural Center.[3, 6]

A weighing lysimeter is a sensitive piece of equipment that is able to measure ET of plants on an hourly, daily, and seasonal basis.

The lysimeter at the Kearney Ag Center is comprised of a large soil container (2m wide, 4m long, and 2m deep) that sits upon a scale. The soil surface of the container is at the same level as the soil level of the vineyard surrounding it. Therefore, the soil container and scale are below ground.

Two grapevines were planted in the lysimeter in 1986. Vines were also planted around the lysimeter with vine and row spacings of approximately 7 1/2 and 11 1û4 ft, respectively. The trellis system used for the vines is a two-foot crossarm approximately five feet above the soil surface. The scale has a resolution of 0.2 mm of water, which is less than 0.5 lbs.

As water is lost from the tank, either by evaporation from the soil or transpiration from the vines, a datalogger records the loss in weight (i.e. it measures ET_c) hourly. The vines within the lysimeter are automatically irrigated whenever they use 2 mm of water (slightly more than two gallons) and are therefore assumed not to be under water stress.

Water use of the vines in the lysimeter, between budbreak and the end of October, from four years after planting until the present, has ranged from 29 to 34 inches (approximately 1,400 to 1,700 gallons per vine).[6] Potential ET at the same location over the same years has ranged from 42 to 47 inches. Daily water use of vines growing within the lysimeter will average 10 to 12 gallons at maximum canopy, mid-summer.

During the 1998 and 1999 growing seasons, a study was conducted to determine the relationship between leaf area of the vines in the lysimeter, shaded area cast on the ground at solar noon, and grapevine water use. Thus, leaf area was estimated and shaded area on the ground was determined at various times throughout the growing season.

The study found that, at full canopy, shaded area on the ground comprised approximately 50% of the total land area allocated per vine within the vineyard.

In 1999, the shoots of the two vines growing within the lysimeter were allowed to grow across the row middles on either side of the lysimeter. The shaded ground area just prior to that time was about 60%. A support system was then constructed to raise the shoots (simulating an overhead trellis system) and the percent ground cover increased to approximately 75%.

Actual vine water use prior to raising the canopy was 12.7 gallons per day, and after raising the canopy, it increased to 16.7 gallons per day. This indicates that it was the orientation of the canopy (determined by the trellis system) and not the total leaf area per vine that dictated how much water the vine used, if the vine was not water-stressed.

It was also found that vine water use (ET_c) and the crop coefficient were linear functions of the amount of shade measured beneath the vines at solar noon. The equation to describe the relationship between the crop coefficient (k_c) and percent shaded area was: $k_c = 0.002 + 0.017x$, where x is percent shaded area.

A linear relationship between the crop coefficient and light interception (or shaded area), with a slope similar to that of the grapevines, has also been found by Dr. Scott Johnson for peach trees growing in a weighing lysimeter at the Kearney Ag Center.

There are several reasons why grapevine water use and the crop coefficients may be related to the percentage of shaded area when measured at midday:

1) The driving force of ET, net radiation, is greatest between 11am and 2pm.
2) Approximately 75% of the daily water use by vines growing in the lysimeter occurs between 10am and 2pm.
3) The shade beneath a vine is an indirect measure of how much solar radiation the vine is intercepting.
4) The shade beneath the vines varies only slightly between 9am and 3pm for east/west rows (row direction in the lysimeter vineyard).
5) As the season progresses, the vine's canopy gets larger, resulting in more light being intercepted (more shaded area on the ground) and greater water use.

Impact of trellis and row spacing

There are numerous trellis systems used for winegrape production in California today. There are systems in which little management is used (sprawl systems) and those, which are highly manipulated. The latter systems include the VSP (vertical shoot positioned trellis) and vertically divided canopies such as the Scott Henry or Smart/Dyson trellises. Horizontally divided canopy trellis systems include the lyre, U and Wye trellises, and the GDC (Geneva Double Curtain).

Any of the above winegrape trellis systems that increase the percent ground cover should also increase vineyard irrigation requirements based upon observations using Thompson Seedless grapevines in the lysimeter.

In addition, as the tractor-row width decreases, the percent ground cover or shaded area will increase. One would therefore assume that vineyard water use would increase as the distance between rows decreased.

I have independently developed crop coefficients for two different training/trellis systems: a VSP trellis with unilateral cordons and a modified GDC trellis with quadrilateral cordons trained to a four-foot crossarm. In order to develop kcs for both systems, water was applied at various fractions of my initial estimate of ETc for each trellis system. This was replicated in trials in two commercial vineyards.

The fractions of ET_c used were 0.25 to 1.25 ETc in increments of 0.25. The VSP-trellised vineyard was in Carneros and had a seven-foot row spacing and the quad-cordon vineyard in Temecula had a 12-foot row spacing.

A vine water balance was then determined for each irrigation treatment. Water inputs from rainfall and irrigation and the soil water content in each irrigation plot were measured.

Based upon my work at the Kearney Ag Center, if vines are irrigated at full ET, soil water content will remain fairly constant. If vines are being deficit-irrigated, then soil water content will decrease. In addition, my previous work with Thompson Seedless indicated that midday leaf water potential generally would not be more negative than –10 bars if vines were irrigated at 100% of ETc.

These were the two main criteria used to determine if vines were receiving applied water amounts that replaced water used by the vines on a weekly basis. Once it was determined which irrigation treatment (applied water amount) was equivalent to vine ET_c, I was able to calculate how much water the vines used at regular intervals throughout the growing season and then to calculate seasonal crop coefficients.

The maximum k_c for the vines on a VSP trellis system, in a vineyard with a seven-foot wide tractor row, was slightly greater than 0.7 (Table I). The maximum k_c for the modified GDC trellis (12-foot wide tractor row) was approximately 0.75 (Table II). Both of the above values are less than that found for Thompson Seedless grapevines in the lysimeter where the maximum kc can be close to 1.0.[3]

The VSP trellis seasonal crop coefficients initially developed on the seven-foot wide row spacing have been tested in other commercial vineyards with different row spacings, row directions, cultivars and rootstocks, and at four different locations. At all locations, irrigation treatments at various amounts of estimated full ET_c were included in a replicated trial.

The seasonal VSP trellis crop coefficients were adjusted either upward or downward for narrower or wider row spacings, respectively, from those developed in Carneros.

For example, the seasonal k_cs for a six-foot row spacing were increased by 1.17, relative to those developed in Carneros on a seven-foot row spacing (7 ft ÷ 6 ft =

1.17) while those for a 10-foot row spacing were decreased by 0.7 (7 ft ÷ 10 ft = 0.7) relative to those developed in Carneros (Table I). Therefore, the maximum k_c for VSP vineyards with tractor row widths of six feet, eight feet, nine feet, and 10 feet, were calculated to be 0.82, 0.62, 0.55, and 0.49, respectively (Table I).

Crop coefficients developed for the VSP trellis will increase or decrease water use per unit land area as row spacing decreases or increases. However, if vine spacing within the row is the same among those vineyards, then water use per vine will remain the same. An example of this can be found in Table II. The water use per unit land area (ET_c in inches column), comparing a VSP trellis at six- and nine-foot row spacings is greater for the six-foot row vineyard but water use per vine (last column) is the same for both.

In order to validate my assumptions about row spacings and crop coefficients used, the crop coefficient was considered appropriate (i.e. applied water amounts replaced what the vines used) if midday leaf water potential remained above –10 bars all season and if berry weight was maximized at applied water amounts at 75% of estimated full ET_c (i.e., applied water amounts at greater values did not result in a further significant increase in berry size.) These parameters were based upon data collected on Thompson Seedless in San Joaquin Valley.

At various points during the 1998 and 1999 growing seasons, shaded areas under vines at all trial sites with VSP trellises, were measured at solar noon.

This was done by placing a four-foot by four-foot piece of plywood, on which a grid (six-inch by six-inch squares) had been drawn on the ground beneath the vines and either visually estimating the percent shade in each square of the grid or by recording an image of the plywood with a digital camera. The image was downloaded to a computer and the shaded area was determined with appropriate software.

Crop coefficients used to schedule irrigations that week in each vineyard were compared with the crop coefficient calculated as a function of shaded area measured that particular week. The equation used was: k_c = 0.017 x percent shaded area, where 0.017 is the slope of the equation describing the relationship between the percent shaded area and the crop coefficient of Thompson Seedless vines growing in the weighing lysimeter.

The data indicated that the kc calculated from percent shaded area and the k_c being used that week to schedule irrigations were linearly correlated with one another (coefficient of determination [r^2] was 0.86). This also implies that the use of the shaded area technique to calculate a crop coefficient could be a viable tool in vineyard irrigation management to approximate the value of potential vine water use at full ETc.

In the 2000 growing season, crop coefficients were developed for vineyards using a lyre trellis and a high-density VSP-trellised vineyard (the latter planted 1m x 1m; 4,049 vines per acre), using the shaded area technique.

The calculated k_c at maximum canopy development (i.e. late in the summer) was 0.83 for the lyre (planted to nine-foot wide tractor rows) and 0.91 for the 1m x 1m planting (Table II).

Results indicate that trellises such as the lyre, which spread the canopy, will have higher per vine and per unit land area water requirements than trellises that don't (such as the VSP), when both are planted to with same tractor row width.

However, when there is a VSP trellis in a vineyard with a closer row spacing (such as a six-foot vine row spacing or 1m x 1m planting), water use per unit land area of those vineyards may be comparable to the lyre planted on nine-foot or wider row spacing. This illustrates that both trellis (or canopy type) and row spacing will determine percent ground cover in the vineyard and ultimately potential vineyard water use.

Also during the 2000 growing season, the shaded area was measured beneath vines on vertically split canopies (such as the Scott Henry and Smart/Dyson systems) to derive their crop coefficients. Vineyards in which these systems were used included row directions east/west and north/south.

Shaded area measurements taken at solar noon on a vertically-split trellis planted to north/south rows were not similar to those planted to east/west rows.

I subsequently determined that the shaded area of a vertically split canopy planted to north/south rows measured an hour before or an hour after solar noon was very similar to the shaded area of rows oriented east/west when measured at solar noon.
I also have found that crop coefficients developed on east/west rows were appropriate for north/south rows for both VSP trellises and vertically-split canopies.

The water requirement of a vertically-split canopy is approximately 25% greater than that of a VSP canopy, when planted on the same row spacing when the calculations are made after veraison (Data was generated during the 2001 growing season).

Table III — Calculated water use of Cabernet Sauvignon grapevines in Paso Robles during the 2000-growing season. Potential ET (ET_o) was obtained from the Paso Robles Vintners and Growers Association's PR1 weather station. Row spacing was 10 ft. and vine spacing was 6 ft. (726 vines per acre). It was assumed that there were 27,500 gallons per acre-inch.

Month	Week	ET_o (in.)	K_c	ET_c (in.)	ET_c (gal./acre)	ET_c (gal./vine)	Rain (in.)
May	1	1.38	0.14	0.19	5,225	7.2	0
*	8	1.38	0.17	0.23	6,325	8.7	0
	15	1.50	0.18	0.27	7,425	10.2	0
**	22	1.69	0.22	0.37	10,175	14.0	0
	29	1.89	0.25	0.47	12,925	17.8	0
June	5	1.61	0.28	0.45	12,375	17.0	0.2
	12	1.73	0.32	0.55	15,125	20.8	0
	19	1.69	0.36	0.61	16,775	23.1	0
	26	1.97	0.39	0.77	21,175	29.0	0
July	3	1.57	0.41	0.64	17,600	24.2	0
	10	1.61	0.43	0.69	18,975	26.1	0
	17	1.97	0.44	0.87	21,450	29.5	0
***	24	2.05	0.44	0.90	24,750	34.1	0
	31	2.05	0.45	0.92	25,300	34.8	0
August	7	1.89	0.46	0.87	23,925	33.0	0
	14	2.05	0.47	0.97	26,675	36.7	0
	21	1.73	0.48	0.83	22,825	31.4	0
	28	1.26	0.49	0.62	17,050	23.5	0

*, **, and *** denote dates of the initiation of irrigation, approximate date of bloom, and approximate date of veraison, respectively. Vines were harvested September 27, 2000.

Practical use of measuring shaded area in your vineyard

As shown above, the shaded area beneath vines in your vineyard can be determined by several methods. One can use a grid and then estimate the amount of shade within each grid, then calculate the total shaded area of the vine. The same grid can be used to produce images of the shade on plywood with a digital camera.

There are software packages that allow calculation of areas of different colors on the image. However, the digital camera cannot be used if the vine's canopy extends to the soil surface. Lastly, one can use a tape measure to determine the average width of the shade beneath the grapevine and then calculate the total shaded area. This can be done where the canopy within the vineyard is highly uniform.

It should be noted that determining the shaded area of canopies early in the growing season or in newly planted vineyards is difficult with a measuring tape since such canopies are very discontinuous. It would be hard to get an average width of the shaded area.

However, if one can obtain a good approximation of the amount of shade under the vine, then estimation of a crop coefficient would prove useful in determining the amount of water a vine would use at 100% of vineyard ET.

Below is an example of how potential vineyard water use could be derived using percent shaded area to estimate the crop coefficient:

A. Tractor row width = 10 feet
B. Vine spacing = 6 feet
C. Area per vine = 60 ft^2
D. Average width of measured shaded area between two vines = 3 feet
E. Shaded area per vine = B x D = 6 ft. x 3 ft. = 18 ft^2
F. Percent shaded area = E ÷ C = 18 ft^2 ÷ 60 ft^2= 0.3 or 30%
G. Crop coefficient (k_c) = F x 0.017 (slope of relationship between k_c and percent shaded area of Thompson Seedless) = 30 x 0.017 = 0.51
H. Vine water use = ET_o (obtained from CIMIS) x k_c.

Irrigation scheduling

To determine a vineyard's irrigation requirement, the equation in H above can be used ($ET_c = ET_o \times k_c$). Remember this equation is for calculating applied water volumes that replace amounts of water the vineyard uses daily or at other intervals. That is, the soil's water reservoir would not be depleted. The above equation will give full crop water use in mm or inches.

To determine water application amounts per vine or to calculate pump run times, one must convert mm or inches into liters or gallons. The metric conversion is one mm covering one hectare equals 10,000 liters. The English conversion is one inch covering one acre equals approximately 27,500 gallons.

Once the amounts have been determined, divide the liters or gallons required per unit land area by number of vines per hectare or acre (Tables II and III). The pump run time is also dependent upon the number and sizes of emitters per vine and the irrigation system's emission uniformity.

The seasonal progression of vine water use for a VSP trellis, planted with 10 foot-wide tractor rows is shown in Table III. The data illustrate how vine water use is lower early in the season due to a smaller canopy.

Once the canopy is established and fills the trellis (beginning the middle of July), differences in ET_o from week to week, will result in differences in vine water requirements when this technique to irrigate vines is used. Thus, the benefits of calculating vine water use with this method is that both evaporative demand (ET_o) and the seasonal progression of a canopy's development or trellis type and tractor row spacing dictate how much water to apply.

The following illustrates how seasonal vineyard water use of one trellis system may vary as functions of row spacing and of different trellis systems at the same location.

The calculated vineyard water use between budbreak (April 3) and harvest (September 21) in 2000 for a Cabernet Sauvignon vineyard, using a VSP trellis and a six-foot tractor row near Oakville in Napa Valley, was 17.7 inches and applied water was 89% of that value. Potential ET for the same timeframe was 34.4 inches.

The calculated water use for a similar vineyard but with tractor row widths of 7, 8, 9, and 10 feet would have been 15.2, 13.3, 11.8, and 10.6 inches, respectively. Calculated water use for a lyre trellis, with 9-foot row spacing, and a 1m x 1m planting at the same location would have been approximately 20 inches and 25 inches of water, respectively.

Effect of water amounts on growth and yield

Research conducted in my laboratory and elsewhere, indicates that deficit-irrigation will have minimal effects on berry growth or yield and with possible advancement in date of harvest and an increase in fruit quality.

In each of my irrigation trials, irrigation amounts that are fractions of estimated full ET have been included. These amounts are applied from the first irrigation of the season up until at least harvest or beyond. This allows determination of the effects of both under- and over-irrigation on vine growth, berry characteristics, and yield of raisin and table grapes or wine quality of wine grape cultivars.

I have found that irrigation amounts, at approximately 80% of full ET, maximize berry size for raisin and table grapes.[6] Yield of Thompson Seedless vines grown at the Kearney Ag Center is maximized at applied water amounts that are 80% of lysimeter water use whether used for raisin[5,6] or table grape production (unpublished data).

Table IV — Relative berry weight as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

Location	Cultivar	Irrigation Treatment (fraction of estimated ET_c) 0.25	0.5	0.75	1.0	1.25
		—— (percent of maximum weight)* ——				
Oakville	Cabernet	83	93	98	100	98
Paso Robles	Cabernet	78	88	95	98	100
Gonzales	Chardonnay	77	89	96	98	100
Edna Valley	Chardonnay	82	89	97	99	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%.

Table V — Relative yield as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

Location	Cultivar	Irrigation Treatment (fraction of estimated ET_c) 0.25	0.5	0.75	1.0	1.25
		—— (percent of maximum weight)* ——				
Oakville	Cabernet	77	96	100	99	99
Paso Robles	Cabernet	61	70	81	91	100
Gonzales	Chardonnay	65	81	87	89	100
Edna Valley	Chardonnay	92	90	92	98	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%.

Table VI — Relative pruning weight as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

Location	Cultivar	Irrigation Treatment (fraction of estimated ET_c) 0.25	0.5	0.75	1.0	1.25
		—— (percent of maximum weight)* ——				
Oakville	Cabernet	85	89	100	96	99
Paso Robles	Cabernet	61	67	79	88	100
Gonzales	Chardonnay	75	81	87	96	100
Edna Valley	Chardonnay	87	87	92	98	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%.

It has been found that the yield of Thompson Seedless grapevines used for raisin

It has been found that the yield of Thompson Seedless grapevines used for raisin production actually decreases when applied water is greater than 100% of ET, determined with the weighing lysimeter. This is due to reduced bud fruitfulness and lower cluster numbers per vine.

Vegetative growth of Thompson Seedless vines generally increases as applied water increases from no irrigation to 120% of ET.[5,6]

My studies in various table grape vineyards, in both the Coachella and San Joaquin Valleys (over a four-year period), have demonstrated that packable yields may be only slightly reduced at applied water amounts equal to 50% of full ET.

It should be noted that the above results were obtained in vineyards that were irrigated daily. Therefore, the irrigation frequency used in those studies may have mitigated possible negative effects of deficit irrigation.

My studies in Chardonnay and Cabernet Sauvignon vineyards in Napa Valley and along the central coast of California have somewhat mimicked results found with Thompson Seedless vines. In these studies, irrigation frequency is only once or twice per week. Berry size is usually maximized with applied water amounts at 75% of estimated full ET (Table IV). Yields are slightly diminished at applied water amounts at 75% of full ET (Table V).

Yields have been maximized, in some instances, at applied water amounts equal to 50% of full ET, but this is dependent upon weather (years in which rainfall may have occurred late into the spring), location, soil type, and rooting depth. Pruning weights, a measure of vegetative growth, generally increased as applied water amounts increased (Table VI).

My wine grape studies have also addressed the effect of rootstock on vine water use. At least three rootstocks were used at each site (five in Paso Robles) and these included 5C, 110R, 3309C, Freedom, 140R, and 1103P.

I have found no differences in vine water use or vine water relations among individual rootstocks at a specific location. This may be due to the fact that all vineyards utilized the VSP trellis system. Shoot hedging and positioning, as performed for the VSP trellis, does not allow possible differences in vine vigor (increased canopy size) among rootstocks to be expressed. In addition, drip irrigation may limit exploration of the soil profile by each rootstock.

While, I have rarely found significant interactions between rootstocks and irrigation amounts among the different fruit and yield parameters measured at each site, I have found significant differences in those parameters among rootstocks.

Small wine lots have been made of Cabernet Sauvignon grown at Oakville and

Paso Robles and Chardonnay from Carneros with sensory analysis performed on each. While deficit irrigation will increase color of wine made from Cabernet Sauvignon, there has been no consensus as to preferences among the irrigation treatments.

One possible reason is that irrigation amounts that I calculate as full ETc for the VSP trellis are much less than previously thought. For example, calculated ET_c for the Paso Robles Cabernet Sauvignon vineyard (with 10-foot wide tractor rows) from budbreak to the end of September has only been between 10 to 12 inches per growing season. This is much less water than many growers presently apply.

Conclusions

Information regarding the use of a pressure chamber and estimation of crop coefficients presented above can provide growers an objective means in determining when irrigations should commence, while also helping them estimate how much water a vine potentially may use at full ET_c.

I have used both the pressure chamber and measured soil moisture content with a neutron probe in studies to determine when irrigations should commence. Both have worked extremely well.

However, the measurement of a vine's leaf (or stem) water potential may be preferable, since it integrates the amount of water the vine's roots have access to throughout the soil's profile. In addition, measurements of leaf water potential can be made at more than one site within the vineyard with relative ease.

Many times, determination of a vineyard's soil water status with a neutron probe in a commercial situation is based upon just one access tube per vineyard. Placement of this single assess tube in the vine row, including distance from an emitter (if drip irrigation is used), may not accurately determine soil water status of an individual vine nor account for variability within the vineyard due to different soil types and/or rooting depths.

Calculation of irrigation requirements using crop coefficients and ET_o, provides an objective means to determine how much water should be applied based upon the vine's growth characteristics, trellis, and row spacing. It is also reflective of changes in evaporative demand from day to day during the growing season and from year to year.

For example, if evaporative demand is high one week, irrigation requirements will be high, if it is lower the next week, then irrigation requirements will be lower.

Initiating vineyard irrigation later in the growing season or the use of deficit irrigation may restrict excess vegetative growth, whether for grapevines grown in the interior valley of California or along the coast. This would minimize the cost of canopy management for vines that, in the past, became too vigorous due to excessive irrigation.

Grapevines can be deficit-irrigated at various fractions of estimated full ET_c with minimal impacts on yield but with a potential to increase fruit quality. Thus, in most cases, one may not have to apply water amounts that meet or exceed estimated vineyard water use requirements presented in this article.

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