REGULATED DEFICIT IRRIGATION MANAGEMENT FOR WINEGRAPES

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Introduction

"Appropriate irrigation scheduling" is an axiom whereby irrigations are scheduled to apply an optimum quantity of water that maximizes productivity. This often results in maintaining soil water content near field capacity. Shortages of water, increased costs of irrigation and the incidence of disease have traditionally been the limiting factors to over irrigation in most annual and perennial crops. However, in the production of winegrapes, it has long been recognized that water deficits can lead to improved fruit quality—especially in red wine varieties. Typical strategies to achieve water deficits were developed using surface irrigation and relied on irrigation cutoff to limit water as the fruit ripened. This resulted in both successes and failures depending on the timing of the cutoff, climatic and soil storage conditions.

Precision micro-irrigation has played a major role in reducing the applied water required in winegrapes by improving emission uniformity. Low volume technology made possible new irrigation strategies which can further increase water savings as well as improve fruit quality. Vine water status plays a large role in determining the final composition of the fruit, impacting various solutes such as sugar and organic acids which establish the potential of the fruit to make quality wine.

In recent years it became clear that maintenance of a moderate plant water deficit can improve the partitioning of carbohydrate to reproductive structures such as fruit and also control excessive vegetative growth (Chalmers, *et al*., 1981), giving rise to what has been termed by Chalmers *et al.* (1986) as 'regulated deficit irrigation' (RDI).

Regulated deficit irrigation (RDI) is a term for the practice of regulating or restricting the application of irrigation water limiting the vine water use to below that of a fully watered vine. By restricting irrigation water volumes, soil water available to the vine becomes limited to a level where transpiration exceeds water absorption. It is at this point that the vine begins to undergo a water deficit. RDI can be a consistent reduction (i.e., consistent reduction of planned irrigation volumes over the entire season) or a variable reduction over the irrigation season to induce the desired vine response at the appropriate time.

Achievement of successful RDI requires accurate soil moisture or plant 'stress' sensing, the ability to estimate crop demand, and the ability to irrigate frequently. As pointed out by Jones (2004), a disadvantage of RDI is that it requires water status to be maintained accurately within a rather narrow tolerance; any excess application loses the advantage of the regulated deficit and can cost more in terms of water used, while any under-application can lead to yield or quality losses.

Regulated Deficit irrigation can be a component of a “standard” irrigation strategy or utilized in a “drought strategy” to curtail vine water use during periods of limited water availability.

Vine Water Deficits Caused by Reduced Soil Water Availability

As soil available water becomes limited through vine depletion of winter-stored soil water or irrigation water, a level of availability is approached where the vine cannot sustain the full potential water use. It is at this point that the vine begins to undergo a water deficit. Essentially, a deficit occurs when the water absorption lags behind transpiration.

Under normal early-season conditions, (1) water is readily available in the root zone, (2) the vine is not at full canopy expansion, and (3) the atmospheric-driven demand is small. Therefore, under normal early season conditions, water deficits are uncommon in most winegrowing regions of California. As the season progresses without irrigation, the canopy expands, climatic demands intensify and the soil is further depleted of available water. It is at this time that the vine’s water demand can exceed water uptake from the soil causing water deficits. Cooler growing regions and a greater volume of available water in the soil from winter storage or irrigation will cause water deficits to be postponed until later in the season. Generally, water deficits do not *begin* to occur until the vine has extracted about 50 percent of the available soil water contained in the root zone. Soil depth, texture and the total water stored in the root zone as well as the severity of the climatic demand can influence this rule of thumb.

As water deficits begin, they occur only for a short period of time at the peak water demand period of the day. Initial vine response to water deficits is to reduce the the stomatal aperature, pores in the undersides of the leaf, to limit leaf water loss which creates a better balance between transpiration and water absorption.. Additional recovery occurs when atmospheric conditions moderate in the later part of the day and during darkness hours. This cycle continues each day, influenced by the climate, available soil moisture and to some extent, root extensiveness. Without irrigation, the water deficits become longer in duration and more severe as the season progresses.

Vine Water Status: a Measure of Water Stress

Vine water status of leaves is measured using a pressure chamber in which a leaf contained in a plastic bag is placed in the pressure vessel then sealed from the atmosphere with the petiole exposed. The amount of pressure required to exude the xylem sap out of the petiole is termed leaf water potential. Well watered grapevines undergo significant fluctuations in leaf water potential during the day—from a predawn level of -3 bars to midday levels of -6 to -9 bars depending on the severity of the evaporative demand. Midday levels are typically used for comparison since they plateau for a few hours around noon.

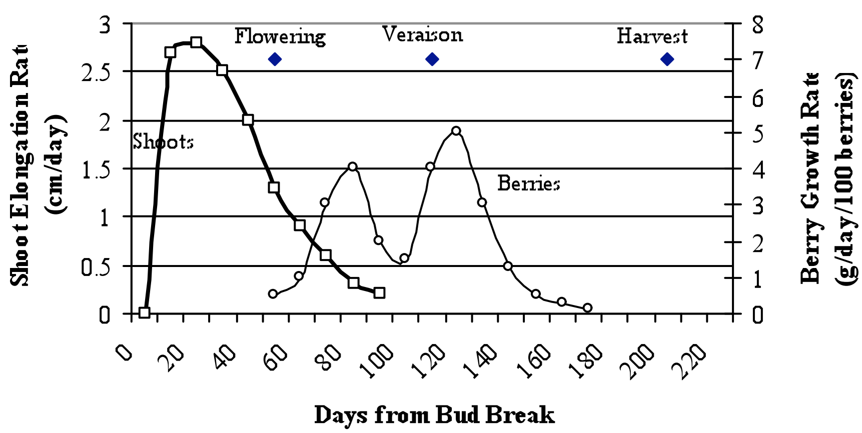
The two primary factors determining water status of vines are the availability of soil water and evaporative demand. Once soil water is limited, water is lost from the leaves resulting in more negative midday leaf water potential. Midday leaf water potential of -10 to -14 indicates levels of low to moderate water stress.

Timing of Water Deficits and Growth Stages

The time of the season vine experiences water stress and the level of stress determine the effects on the vines and fruit. Moderating the severity of water deficits through stomatal closure works well initially, generally limiting the effects of water deficits to a reduction in vegetative growth. As water deficits increase in severity and duration, the stomata are closed for longer periods of time. Since the stomata are the entry points for carbon used in photosynthesis, severe water deficits limit the time the stomata are fully open which in turn limits photosynthesis and the production of sugar.

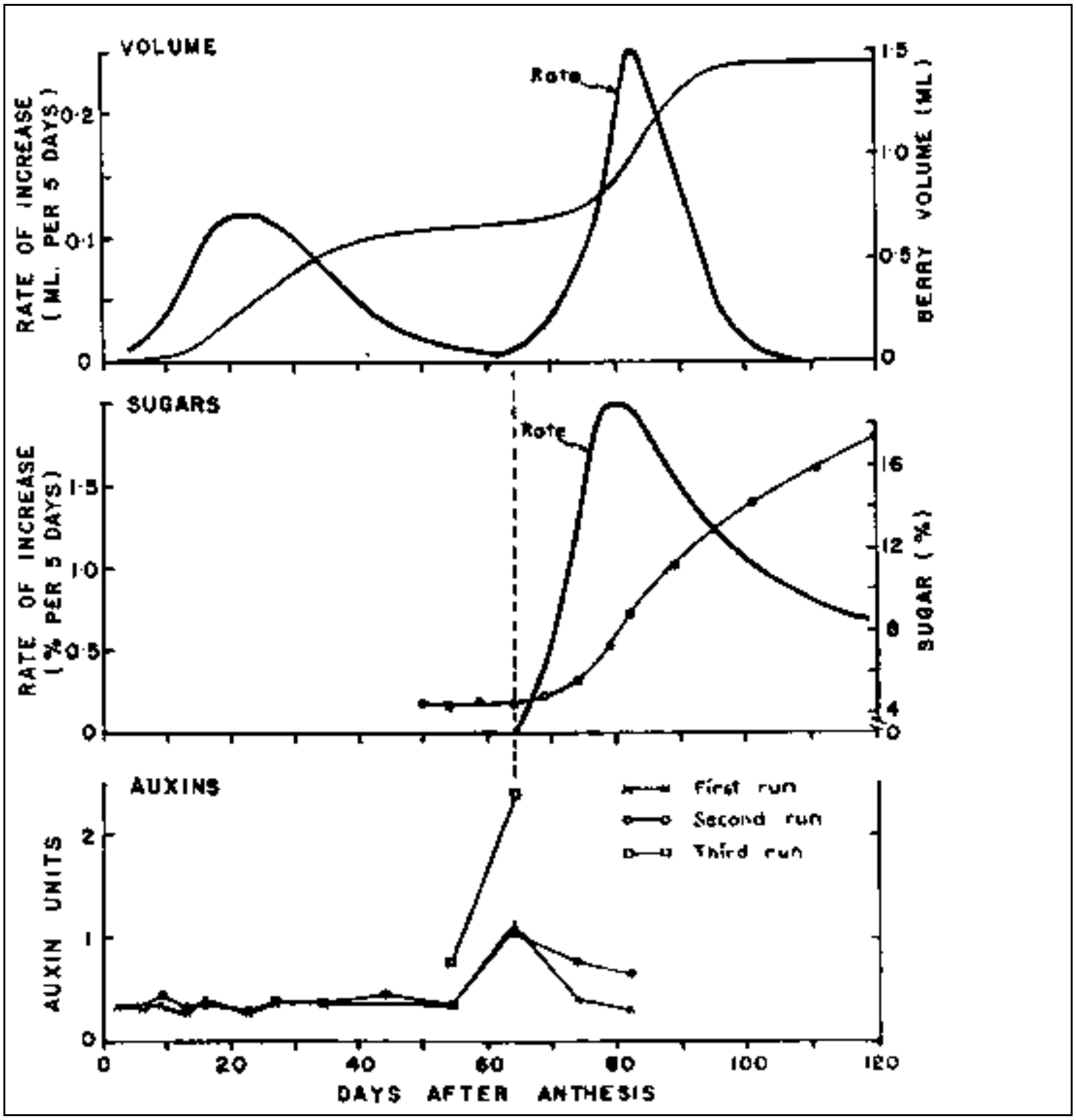
The growth of shoots and leaves begins shortly after bud break. Vegetative growth proceeds at a high rate then declines to near zero as veraison, the onset of fruit color development and softening, is approached (Figure 1). Nearly one-half the shoot length is attained by flowering. Berry growth rate increases after fruit set in an initial rapid period of growth (Stage I). In Stage II, growth rate is much slower followed by another rapid growth period (Stage III) near veraison. Vegetative growth rate of the shoot continues to decline in berry Stage I and is virtually non-existent during Stage III.

Figure 1. Growth rate of various organs of Colombard grapevines, after Van Zyl (1984)



Berry ripening begins at veraison. The berries begin to soften, change color and begin to accelerate in growth during this third and last stage of growth (Stage III). Berries decrease in titratable acidity (TA) and increase in pH and soluble solids (brix) (Figure 2). If water is abundant, lateral shoot growth can continue during this period.

Figure 2 Berry growth rate and size for Seedless Emperor and accumulation of sugar and its rate during fruit growth (Coombe, 1960)



Most soils can provide adequate water for basic shoot growth, root growth, and berry cell division up to a month before veraison (beginning of Stage III). During berry development (Stage II), for a 3-week period leading up to veraison, water deficits can reduce main and lateral shoot growth Depending on the trellis-training system, 2-5 m2 of leaf area per unit canopy length is optimum. Limiting growth of the main shoot and laterals provides more light to the fruit, increasing anthocyanins and phenolics for increased wine color and character. Another way to access adequate shoot growth is to determine the leaf area per weight of fruit. Between 0.8 – 1.2 m2/kg fruit for a single canopy and 0.5 -0.8 m2/kg for divided is considered optimal (Kliewer and Dokoozlian, 2005).

Early Season Deficits

Under normal early-season conditions, (1) water is readily available in the root zone, (2) the vine is not at full canopy expansion, and (3) the atmospheric-driven demand is small. Therefore, under normal early season conditions, water deficits are uncommon in most winegrowing regions of California.

Pre-Veraison Deficits

As the season progresses without irrigation, the canopy expands, evaporative demand increases and the soil is further depleted of available water. At this time the vine's water demand can exceed water uptake from the soil causing water deficits. Regions with lower evaporative demand and a greater volume of available water in the soil from winter storage or irrigation will cause water deficits to be postponed to later in the season. Moderate water deficits at this time can control expansive vegetative growth while allowing photosynthesis to continue unabated. This is the basis for successful Regulated Deficit irrigation strategy.

Post-Veraison Deficits

Canopy size and climatic conditions drive water use at its maximum rate at this time. Even vineyards with the largest soil resource and cool climate will experience water deficits without irrigation. Moderate deficits are necessary during this period to deter the resumption of shoot growth. Recent research supports less sever deficits during the last few weeks prior to harvest. This is especially the case when harvest timing is predicated on extended maturation.

Postharvest Deficits

Water deficits at this time do not affect the current year's crop however severe deficits at this time can lead to low vine carbohydrate reserves and negatively affect bud and cluster development the next season. The post harvest root flush period requires soil moisture for the roots to expand. Trunk and root growth is responsive to excess photosynthate after harvest. If vines become defoliated a short time after harvest, it is questionable whether to apply water because under certain conditions, shoot growth may occur.

Effect of Water Deficits

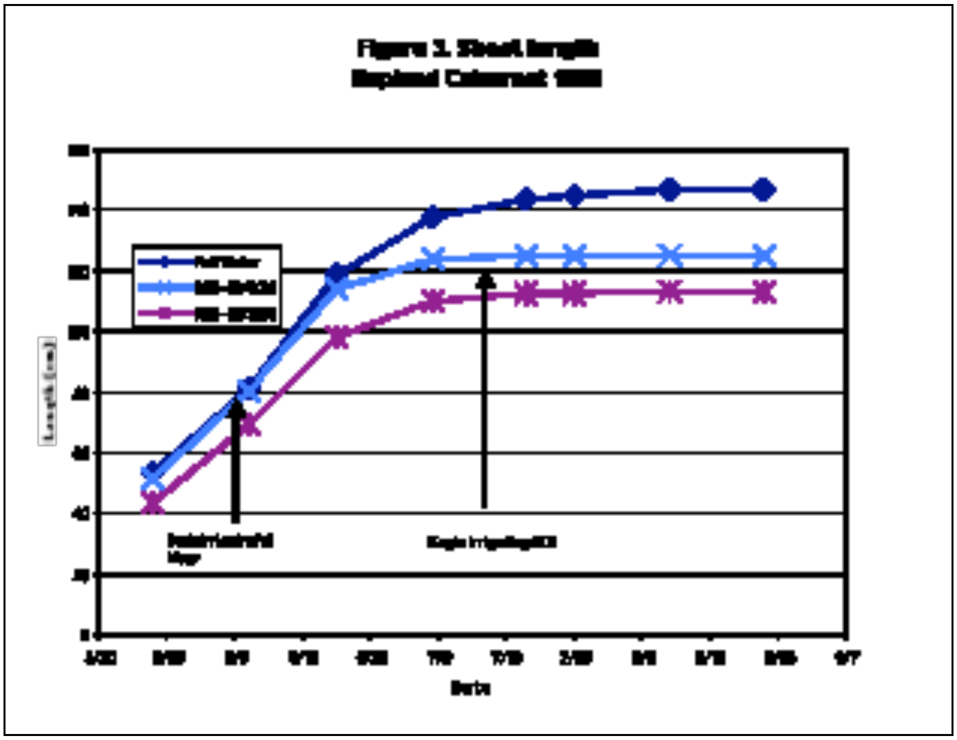
Vegetative Growth

Moderate water deficits inhibit shoot growth and can cause basal leaf drop depending on timing. Both increase the light into the fruit zone promoting fruit color and character. Water deficits occurring early season (bud break to fruit set) are not usually possible in most viticultural regions as previously discussed. Midseason (fruit set to veraison) water deficits are possible in soils that are shallow or coarse textured with limited (soil) water holding capacity. In low rainfall areas and during drought years, midseason deficits are possible even in deep soils. During this period, shoot development (both main shoot length and the number and length of lateral shoots) can be restricted by water deficits (Figure 2). Reduced canopy development can result in reduced leaf area, which may be insufficient to develop and mature fruit in low vigor situations. In years with low amounts of stored water, irrigation during midseason may needed to attain adequate shoot growth. However, when vine vigor provides adequate to more than adequate canopy to support the crop load, restricting or controlling additional canopy (leaf area) is desirable.

More severe water deficits, occurring in the period between veraison and harvest, can result in senescence of lower and interior canopy leaves providing more light to the fruit. Some leaf loss in the fruit zone may occur without significantly reducing sugar accumulation. Moderate amounts of irrigation water during this period can successfully moderate water deficits, causing the desired effect of inhibiting further shoot growth without reducing photosynthesis or causing defoliation. Excessive water deficits can severe cause defoliation, which can lead to sunburn, “raisining” or increased berry temperature, all resulting in reduced fruit quality. Excessive water stress may also result in reduced shoot growth and less fruitful buds the following year. Figure 3 illustrates shoot length over time of a full watered treatment compared to RDI treatments where a leaf water potential of -12 bars was used to initiate the two Regulated Deficit irrigation treatments of 60 and 35% of full irrigation.

Irrigation volumes should be adjusted to moderate, not eliminate, the water deficit late in the season. Excessive irrigation during this period may cause lateral shoot growth to resume, creating a competitive sink for photosynthate, which can increase shading, cause bunch rot in susceptible varieties, delay fruit maturation and harvest. Effects on the wine include increased pH, high malic acid concentrations, poor color/character and vegetal flavors.

A continued or increasing water deficit following harvest provides little or no benefit to the vine and next year’s crop. Root growth, which increases after harvest, can be restricted and can result in early season nutrient deficiencies the following spring. In colder areas, low temperature injury of permanent wood fruiting structures can also result if too little or excessive water is applied post harvest.



Berry Growth

Stage 1 berry growth begins after fruit set and growth progresses at a rapid rate for 40-60 days (Mullins, *et al*., 1992). Berry diameter may double in size. Stage II follows for approximately 7-40 days where the growth rate slows or stops, often call the "lag" phase. The onset of Stage III is marked by veraison lasting until near harvest (typically a 35-55 day period) in which berry growth resumes. Berry growth is less sensitive to water deficits than vegetative growth. However, depending on the timing and severity of water deficits, berry size can be reduced.

Water deficits during Stage I of fruit growth are thought to reduce potential berry size by reducing the number of cells per berry. The reduction in cell number causes smaller berries and almost always causes a reduced yield. As previously mentioned, water deficits at this time are unusual in most winegrape regions of California. However, in years with low amounts of stored water at bud break, irrigation may be needed to prevent significant reduction of berry size and therefore yield reduction.   Water deficits occurring during Stage II (lag phase) or III (cell enlargement) can only affect individual cell size. The common effect of moderate water deficits during these later periods is to slightly reduce berry (cell) size. Severe water deficits near harvest can cause reduced berry size at harvest by dehydration.

Fruit Quality

Potential wine quality is largely determined by the composition of the fruit. The solute composition of fruit at harvest is sensitive to vine water status throughout its development. Moderate water deficits a few weeks before veraison and continuing until harvest can increase the rate of sugar accumulation. If deficits are severe and/or the vine is carrying a large crop, sugar accumulation is generally slowed and further increases in sugar are mostly driven by berry dehydration rather than sugar production. The result is often a fruit with poor balance of solutes and reduced wine quality potential.

Titratable Acidity/Malic Acid

Water deficits result in only moderate decreases in titratable acidity; however, malic acid is likely to decrease sooner with per veraison season water deficits. Deficit irrigation causing moderate water deficits typically reduces malic acid concentrations by one third of a fully watered vine. Increased water stress before irrigation begins, as well as after start of irrigation, further reduces malic acid content (Lundquist *et al.,* 2004) (Table 1). With malic acid declining, the greatest effect of water deficits on the fruit is an increase in the tartaric to malic acid ratio

Table 1. Hopland 1998 Cabernet Sauvignon
Must Analysis

	°Brix	pH	Titratable Acidity (gm/L)	Malate (mg/L)
T1 (100)	23.0	3.37	6.68	3555
T2 (-14/60)	23.1	3.49	4.94	2528
T3 (-14/35)	22.4	3.51	5.39	1450
T4 (-12/60)	23.2	3.43	6.04	2645
T5 (-12/35)	23.0	3.50	5.97	1808
P=	0.4788	0.4152	0.0004	0.0001

Treatments: T1 (100) = full potential water use
T2-T5 = Leaf water potential at irrigation start / RDI %

Phenolics

Phenolics contribute bitterness and astringency in addition to flavors existing in berry flesh and skin. Water deficits and timing of such have a positive influence of the levels of skin phenolics including anthocyanins. Table 2 shows any timing of deficit increased concentrations of skin phenolics and anthocyanins compared to a more fully watered grower standard (Matthews and Anderson, 1988)

Table 2. Skin Phenolics and Anthrocyanins in Cabernet Franc

Treatment	Skin Phenolics mg/cm2	Skin Anthrocynins mg/cm2
Control (grower std)	0.46	0.51
Early Deficit (pre-veraison)	0.56	0.61
Late Deficit (post veraison)	0.52	0.59
Continual Deficit (pre & post veraison)	0.57	0.65

Yield

Reports on the effect of water deficits on yield are varied. Results from research in both California and Australia indicate white varieties (Chenin blanc, Thompson Seedless and Chardonnay) maximize yield at near 60-70% of full potential seasonal vine water use with the remainder of the consumed water supporting increased vegetative growth (Williams *et al*., 1992). More severe deficits result in yield reductions. In red varieties, water deficits at the same level have been shown to decrease vine yield from that of full potential water use by 3 to 19% (Matthews and Anderson, 1989). A trial conducted near Lodi, CA comparing full irrigation to moderate water deficits over four seasons in Cabernet Sauvignon, averaged yield reductions of 19% found. The full vine water use resulted in a 10-ton per acre crop due to increased berry size and fruitfulness. The wine quality of the full vine water use treatment suffered by high pH, reduced color, and character. Additionally, a similar study conducted in Galt, CA using Syrah resulted in an average of 30% reduction from full irrigation due to moderate water deficit regime.(Prichard et.al. 2009)

Yield reductions generally require moderate water deficits to be repeated for one to two years before measurable reductions occur. In the first year of implementing deficit irrigation, yield reduction is a result of reduced berry size only. Table 3 shows the average yield results for the second through fifth year of imposed water deficits in reducing both berry size and fruit load. The reduction in fruit load in the deficit treatments was a result of less fruitfulness or cluster and berries per vine than the full water treatment. Yield reductions in red varieties have been associated with increased fruit quality while full potential water use results in reduced fruit quality expressed as reduced wine color and character. Increasing crop load through pruning and supplying additional water as berries ripen has improved yields while having little effect on fruit quality.

Table 3. Yield and Yield Components
2005-2008 Syrah, Galt

Irrigation	Yield (lbs/vine)	Berry Size (g)	Fruit Load (berries/vine)	Cluster No. (Cl/vine)	Cluster Wt. (lbs/Cl)
I-1	22.1 a	1.52 a	6342 a	57.5 a	0.37 a
I-2	17.0 b	1.29 b	5779 b	53.4 b	0.30 b
I-3	14.1 c	1.20 c	5209 c	47.4 c	0.29 b
P =	0.0000	0.0000	0.0000	0.0000	0.0000

Treatments: I-1 Full Potential Water Use
I-2 -14 bars leaf water potential at irrigation start / 50% RDI to 100% at 19º Brix
I-3 -14 bars leaf water potential at irrigation start / 50% RDI

Developing an Irrigation Strategy Incorporating RDI Principles

Deficit Irrigation is practiced to limit excessive vegetative growth and improve fruit quality or limit water use in times of drought. If neither of these conditions exist alternative irrigation strategies may be more appropriate. An example of this is young developing vineyards, low vigor vineyards whether it is from rootstock/scion selection for the soil resource or nutrition or pest related issues.

When selecting an irrigation strategy it should be designed to accomplish the specific problem, executed, and then monitored to determine its effect. Adjustments can be made in succeeding years to move towards the desired effects.

A strategy to control excessive vigor and open up the canopy so more diffuse light penetrates to the fruit zone generally requires that no irrigation be applied until shoot growth is under control as a result of reduced water availability in the root zone. Using visual clues or measuring leaf water potential is a successful method of allowing the vines to experience moderate water deficits before irrigating. Measuring water potential also can indicate when water stress is too high so irrigation can forestall canopy/fruit damage.

Moderate levels of vine water stress vary somewhat by variety and fruit quality goals. White winegrapes can benefit by reducing vegetative growth, however leaf loss allowing light into the canopy may create more color and character than desired. Red winegrapes on the other hand tend to benefit from more exposure and higher levels of stress. Mid-day leaf water potential of -10 to -13 bars is a typical irrigation start point or "Leaf water Potential Threshold" for a RDI program white winegrapes. Red winegrapes develop desired fruit characteristics with a more severe threshold of -13 to -15 bars. Some varieties of red grapes are more sensitive than others with Merlot being most sensitive followed by Cabernet Sauvignon, and Syrah with Zinfandel of this group being the most tolerant.

Once an irrigation "threshold" is selected the question becomes how much water to apply or a specific RDI. The RDI is a percentage of the full potential vine water use based on climatic demand and canopy size. The selected RDI should be low enough to prevent the resumption of shoot growth and high enough to continue photosynthesis, and prevent excessive leaf loss which could cause the fruit to be sunburned or raisined.

Successful RDI's are typically 50 to 60% of full vine water use. More severe RDI's of 35-40% has resulted in delayed harvest and poor quality fruit in seasons when harvest is late.

<u>Executing the Deficit Threshold RDI Strategy</u>

The first irrigation is made at a specific vine water status which can be measured by leaf water potential. Once the threshold stress level is achieved the volume of water to apply is determined by calculating the full potential vine water use for an irrigation period based on the canopy size then applying a portion (RDI %) of the full water use.

<u>Estimating Full Potential Water Use</u>

The full potential water use varies as a result of climatic conditions and the size of the canopy. The climate factor can be estimated using the reference evapotranspiration (ETo) values, which indicate that vine water use varies over the season. Normal or average year's ETo data (1984-2003) is shown for Lodi, California in Figure 3. Water use is also influenced by vine canopy growth from bud break to full canopy expansion. Canopy growth is accounted for by a modifying factor of the ETo called the Crop Coefficient (Kc) The Kc, which varies from a small value after bud break and increases as the vine canopy expands to maximum size.

Together, these factors (ETo × Kc) contribute to a water use pattern that begins at a low rate in spring, peaks in mid-summer, and then declines as leaf drop approaches. Canopy management practices such as hedging and leaf removal or canopy disruption by machine harvesting can further modify this pattern by reducing the solar energy interception by the vine and therefore the Kc. When considering the water use of a single vine, a larger canopy will have a larger leaf area exposed to the atmospheric conditions that drive water use and, therefore, that individual vine will have a greater water use.

When estimating the full water use of an area of land planted to winegrapes (ETc), it is necessary to quantify the extent of canopy coverage by measuring the percentage of land surface shaded by the vine canopy. Row spacing can have a significant influence on percent land surface shaded since a closer row spacing increases the land surface shaded by the vines. Trellis design, vine health, and vigor as a result of rootstock/scion combination, soil conditions, pests that affect leaf area or root function, and fertilization can affect the amount of land surface shaded. In addition, vine training, trellis type, and spring growth conditions can influence the rate of canopy expansion thus emphasizing the fact that the percentage of land surface shaded increases as the canopy develops. The variables that affect land surface shading will subsequently affect vine water use

Vine water use increases as the percent of land surface shaded increases. The practical ramifications are that wider spaced rows, young grapevines or low vigor vines with a small canopy have a lesser percentage land surface shaded and use less water on a per- acre basis than vines with a larger canopy.

The percentage of land surface shaded is measured midday (solar noon). The method described in the next section for estimating land surface shading seems to work well with bilateral or quadrilateral trellis systems, but less so when vertical shoot positioned (VSP) vineyards are measured. VSP canopies have the minimum land surface shaded at solar noon when row orientation is north/south and therefore may require a different method to account for the canopy/land surface relationship. Research is currently underway to develop a reliable method for use with VSP and similar trellis systems.

Evapotranspiration Reference Values (Eto)

Evapotranspiration Reference Values (ETo) are calculated using measurements of climatic variables including solar radiation, humidity, temperature, and wind speed and expressed in inches or millimeters of water. A one-inch depth of water use, like rainfall or irrigation water, is equal to 27,158 gallons per acre of land. ETo values most closely approximate the water use of a short mowed full coverage grass crop. Climatic conditions are constantly collected from which ETo values are calculated and made available by CIMIS. The California Irrigation Management Information System (CIMIS) is managed by the State of California Department of Water Resources, which collects, maintains and provides Reference Evapotranspiration (ETo) values from nearly 100 weather stations throughout California. Both historical averages (normal) and real time (current year) values are available.
CIMIS is on the web at: http://www.cimis.water.ca.gov

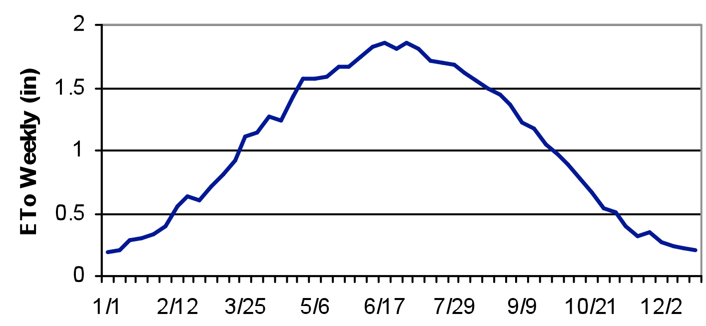


Figure 3. Lodi Eto, 1984 - 2003 Average
CIMIS Stations # 42 and 166

<u>Crop Coefficient (Kc)</u>

The Crop Coefficient (Kc) is a factor, which allows the use of Reference values (ETo) to estimate full grapevine water use (ETc) of a non-water stressed vineyard. Kc values have been experimentally linked to the percent shaded area in the vineyard measured at midday. They can be measured at any time of the season, however when using the Deficit Threshold Method, it is necessary to only measure at the threshold or beginning of irrigation. At that time, canopy expansion is complete. It should be re-measured if canopy reductions occur due to canopy management such as hedging.

Larry Williams (2002) demonstrated in a weighing lysimeter at the University of California Kearney Research and Extension Center that vineyard water use and Kc increases linearly with the percentage of land surface shaded by the crop (Figure 4). He suggests measuring the percent shaded at midday and using the following equation to determine the Kc:

Figure 4. Relationship between land surface shaded and crop coefficient (Kc)

Kc = 0.002 + 17 × the percent shaded area

Simplified Equation: Kc = 1.7 × percent shaded area (e.g., 0.40 for0%)

The procedure would entail measuring the average shade on the floor at midday of (as an example), an 11-foot row spacing with a 7 foot vine spacing. The average amount of shade between two vines is measured at 31 sq ft then compared to the single vine area of 77 sq ft which is 40% of the square foot area of one vine. The Kc is calculated as follows:

Kc= (1.7 x 0.40) = 0.68

Calculating Full Potential Water Use with Historical Average ETo

The best way to illustrate the mechanics of calculating the amount of water to apply is to select an RDI for specific vineyard conditions then use a spreadsheet to incorporate ETo, Kc, RDI, soil moisture use, and effective rainfall into an irrigation schedule. The specific vineyard conditions are:

Variety: Cabernet Sauvignon, mature
Spacing 7 x 11 feet bi-lateral cordon
Leaf water potential threshold of -13 bars reached July 8th
Shaded area: 68% or 0.68
Area: Lodi, CA CIMIS station # 166
Harvest: October 1st

The spreadsheet will be divided into 3 parts to illustrate each step. The first step is to calculate full potential water use of the vineyard.

Figure 5 shows an example calculation of weekly full potential water use for Lodi, CA using the 1984 to 2003 historical average ETo for CIMIS stations #42 and #166. After the -13 bar threshold was achieved (July 8 in this example), the net irrigation requirement can be calculated from the threshold date to the end of the season using average historical ETo values. The Kc used is 0.68 for a 40% midday shaded area. Calculations are made only after the threshold midday leaf water potential (-13 bars) was measured in the vineyard on July 8. The product of ETo and Kc yields the full potential water use.

$$\text{ETo} \times \text{Kc} = \text{Full Potential Water Use (ETc)}$$

Figure 5. Irrigation Scheduling Worksheet - Lodi, CA

ETo are the averages of daily data from 1984 to 2003.
from the Lodi (CIMIS #42) and West Lodi (#166) weather stations

Assumptions
1. Leaf Water Potential trigger was reached July 8th.
2. Harvest Date was October 1.

Date	A = Historical Eto[a]	B = Crop Coefficient[b]	C = A x B: Potential Water Use
Period	Inches/Period	Kc	(in)
Jly 8-14	1.82	0.68	1.24
Jly 15-21	1.720	0.68	1.17
Jly 22-28	1.692	0.68	1.15
Jly 29 to Aug 4	1.676	0.68	1.14
Aug 5-11	1.626	0.68	1.11
Aug 12-18	1.556	0.68	1.06
Aug 19-25	1.494	0.68	1.02
Aug 26 to Sept 1	1.448	0.68	0.98
Sept 2-8	1.368	0.68	0.93
Sept 9-15	1.225	0.68	0.83
Sept 16-22	1.171	0.68	0.80
Sept 23-29	1.054	0.68	0.72
Sept 30 to Oct 6	0.974	0.68	0.66
Oct 7-13	0.883	0.68	0.60
Oct 14-20	0.779	0.68	0.53
Oct 21-27	0.660	0.68	0.45
Oct 28 to Nov 3	0.540	0.68	0.37
Total			14.75

[a] http://wwwcimis.water.ca.gov/cimis **or** http://ucipm.ucdavis.edu
[b] Crop Coeficient calculated based on 40% midday land surface shaded (0.68)

Calculating the Water Use Using the Regulated Deficit % (RDI %)

Once the full potential water requirement is calculated for the vineyard, the Regulated Deficit percent (RDI %) is used to calculate the amount of water the vineyard will use under the RDI % you have selected. In our example, 0.50 or 50 % of full potential water use was selected. Figure 6 shows the full potential water use x RDI% equals the gross amount of water use for the selected RDI%. Notice the RDI % increased to 1 or 100% after harvest as full water is required to encourage root growth and further carbohydrate accumulation.

Figure 6. Irrigation Scheduling Worksheet - Lodi, CA

ETo are the averages of daily data from 1984 to 2003.
from the Lodi (CIMIS #42) and West Lodi (#166) weather stations

Assumptions
1. Leaf Water Potential trigger was reached July 8th.
2. Harvest Date was October 1.

Date	C = A x B: Potential Water Use	D = RDI coefficient[c]	G = [(C x D) - E - F]: Net Irrigation Requirement
Period	(in)	RDI %	(in)
Jly 8-14	1.24	0.5	0.62
Jly 15-21	1.17	0.5	0.58
Jly 22-28	1.15	0.5	0.58
Jly 29 to Aug 4	1.14	0.5	0.57
Aug 5-11	1.11	0.5	0.55
Aug 12-18	1.06	0.5	0.53
Aug 19-25	1.02	0.5	0.51
Aug 26 to Sept 1	0.98	0.5	0.49
Sept 2-8	0.93	0.5	0.47
Sept 9-15	0.83	0.5	0.42
Sept 16-22	0.80	0.5	0.40
Sept 23-29	0.72	0.5	0.36
Sept 30 to Oct 6	0.66	1	0.66
Oct 7-13	0.60	1	0.60
Oct 14-20	0.53	1	0.53
Oct 21-27	0.45	1	0.45
Oct 28 to Nov 3	0.37	1	0.37
Total	14.75		8.68

[a] http://wwwcimis.water.ca.gov/cimis **or** http://ucipm.ucdavis.edu
[b] Crop Coeficient calculated based on 40% midday land surface shaded (0.68)
[c] Regulated Deficit is 50% (0.5)

<u>Adjusting the Schedule for the Current Season's Climate</u>

When real time (the current season) ETo and effective rainfall values become available, they can be substituted into the table to account for the variance from normal ETo values and the actual effective rainfall. Real time ETo and rainfall are available on a one day lag time from the CIMIS network.

The Deficit Threshold Method relies on a calculation using historical ETo data for a one-week period, then applying the indicated amount of water to the vineyard. After the end of that week, the real time data is downloaded and input into the spreadsheet to replace the historical ETo used to develop the last week's schedule. Any differences between the previous week's application volume/time should be adjusted as an addition or subtraction on the new, current week's schedule. For example if 12 hours were applied using the historical ETo values then upon re-calculating using real-time data the amount should have been 11 hours, simply subtract 1 hour from the current week schedule.

In order to react to rapidly changing climate, if an extraordinary hot and low humidity period begins and is expected to last a few days—increase the irrigation volume to try to meet the increase in water use. When recalculating with real time ETo values, the next week's result will indicate your success in estimation.

Accounting for the Soil Contribution and Effective Rainfall.

Soil Contribution (Column E). The soil moisture content declines as the vine extracts moisture from the beginning of shoot growth until the leaf water potential threshold is reached. At this time the vine can still remove additional moisture from the root zone until harvest; the available moisture is at deeper depths, and the rate of extraction is slow. This water must be accounted for as an input to vine water use in column E. Figure7.

In deep (7 ft) medium texture soils, an average amount of water which will be removed from the irrigation start to harvest is typically 2½ inches. On shallower soils, this amount can be as low as 1 inch. Using a calibrated instrument which reads in inches of water per foot of soil, the water content of the root zone can be measured at bud break, the irrigation start and at harvest. These times represent the root zone starting point, the irrigation start, and the dry point respectively. Subtracting the irrigation start moisture content form the bud break content will represent the amount of soil moisture used up until irrigation. Additionally, subtracting the harvest (dry point) from the volume at the irrigation start represents the volume of water the vines will use from that point through harvest.

Table 4 shows the readings typical of a 7 ft depth sandy loam soil in Lodi, California. If soil measurements are not available, use the estimations described above.

Table 4. Total Root Zone Soil Moisture Content

	Inches	Inches
Total Moisture		
A – Bud Break	16.0	
B – Irrigation Start	13.5	
C – Harvest	10.0	
Available Water		
Bud Break	A – C	6.0
Irrigation Start	B – C	2.5

The water that will be used from the threshold to harvest is called the soil contribution. Divide the amount (in this example, 2.5 inches) by the weekly periods from the threshold to the estimated harvest date, July 8 through Sept 30.

2.5 inches / 12 weekly periods = 0.2 inches per period

Figure 7 illustrates the addition of the estimated soil contribution of each weekly period from the threshold to harvest (Column E).

Effective Rainfall (Column F)

Effective rainfall is usually minimal in the period of time from the threshold through harvest. However, significant rainfall is possible and must be accounted for as a water source to meet the calculated vine requirement. The most practical method to estimate effective in-season rainfall for vineyards is using the formula:

$$\text{Effective Rainfall} = [\text{rainfall (in)} - 0.25\text{ in}] \times 0.8$$

This method discounts the first 0.25-inch as lost to evaporation after the event and estimates 80% of the remainder is stored in the soil for vine use

In Figure 7, the effective rainfall (column F) is entered the week beginning October 28. The measured rainfall was 0.65 inches. Calculations are as follows:

$$\text{Effective Rainfall} = [0.65 - 0.25] \times 0.8 = 0.32\text{in.}$$

Notice that the 0.32 inches is nearly equal to that week's calculated vine use and the irrigation volume is reduced to near zero for that week period.

Figure 7. Irrigation Scheduling Worksheet - Lodi, CA

ETo are the averages of daily data from 1984 to 2003.
from the Lodi (CIMIS #42) and West Lodi (#166) weather stations

Assumptions
1. Leaf Water Potential trigger was reached July 8th.
2. Harvest Date was October 1.

Date	**C = A x B: Potential Water Use**	**D = RDI Coefficient[c]**	**E = Soil Contribution**	**F = Effective Rainfall[d]**	**G = [(C x D) - E - F]: Net Irrigation Requirement**
Period	(in)	RDI %	(in)	(in)	(in)
Jly 8-14	1.24	0.5	0.2	0	0.42
Jly 15-21	1.17	0.5	0.2	0	0.38
Jly 22-28	1.15	0.5	0.2	0	0.38
Jly 29 to Aug 4	1.14	0.5	0.2	0	0.37
Aug 5-11	1.11	0.5	0.2	0	0.35
Aug 12-18	1.06	0.5	0.2	0	0.33
Aug 19-25	1.02	0.5	0.2	0	0.31
Aug 26 to Sept 1	0.98	0.5	0.2	0	0.29
Sept 2-8	0.93	0.5	0.2	0	0.27
Sept 9-15	0.83	0.5	0.2	0	0.22
Sept 16-22	0.80	0.5	0.2	0	0.20
Sept 23-29	0.72	0.5	0.2	0	0.16
Sept 30 to Oct 6	0.66	1		0	0.66
Oct 7-13	0.60	1		0	0.60
Oct 14-20	0.53	1		0	0.53
Oct 21-27	0.45	1		0	0.45
Oct 28 to Nov 3	0.37	1		0.32	0.05
Total	14.75		2.40		5.96

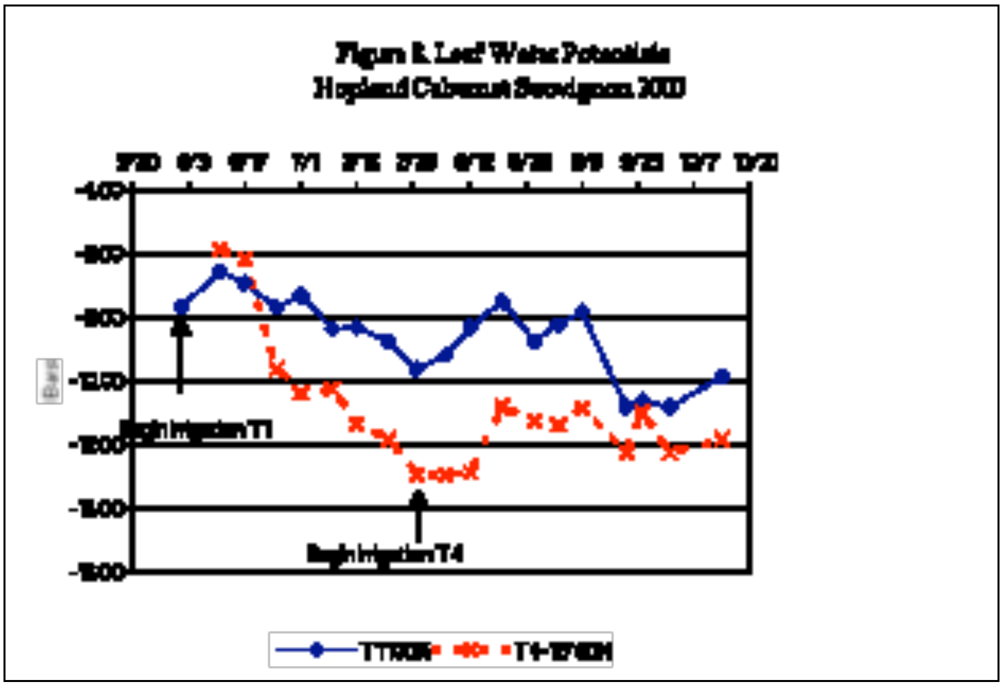
[a] http://wwwcimis.water.ca.gov/cimis **or** http://ucipm.ucdavis.edu
[b] Crop Coeficient calculated based on 40% midday land surface shaded (0.68)
[c] Regulated Deficit is 50% (0.5)
[d] Effective rainfall is calculated from actual rainfall.
Calculations are not shown on this sheet.

Monitoring Performance to Evaluate the Strategy

Measuring vine performance makes it possible to improve the irrigation both during the current year and for the following season. Post threshold measurements of leaf water potential and vegetative growth can be made during the season. Fruit quality, yield components, and maximum shoot length and pruning weights can be measured at harvest.

Post Threshold Midday Leaf Water Potential

Using the deficit threshold method, measurements of vine water status are made to determine when to begin irrigation. The pressure chamber is then used to monitor the vine water status as it is influenced by the irrigation amounts determined by the RDI %. The time to measure vine water status, which is most meaningful, is just before an irrigation event. This measures the maximum water stress before the next irrigation. Figure 8 shows the leaf water potential of various irrigation regimes before and after weekly irrigation events. Post threshold monitoring can be used to determine the effect of the irrigation amounts and to validate the RDI %. Changes can be made to the irrigation volumes if results are inconsistent with expectations. Note that there can be a lag in leaf water potential recovery after significant water deficits as shown after irrigation began in Treatment 4 (Figure 8).



<u>Vegetative Growth</u>

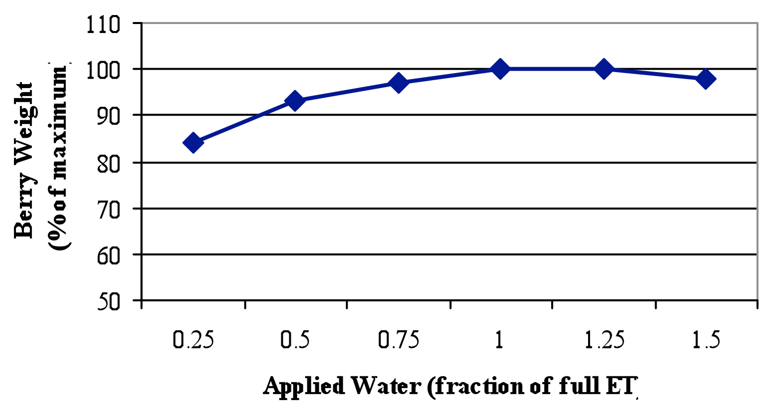
Shoot length measurements are the most common evaluation of vegetative growth. They can be made after veraison, before harvest hedging or at pruning if there is no hedging before harvest. Shoot growth is quite variable, so more measurements will give a better estimate of the average.

Pruning weights are also a good indication of vegetative growth when vines are not hedged at harvest. Typically, the pruning weights of 10 vines per site and 3 sites per block are necessary to achieve a reasonable average. Measurement of spur diameter between the 1st and 2nd buds of a spur is also gaining popularity since pre-harvest hedging is becoming commonplace.

Yield

Yield is typically recorded as the delivered fruit from a block. It is important to keep blocks irrigated by different strategies separate to evaluate the effect of an irrigation regime. Cluster counts on a per vine basis and a berry sample to determine average berry size is more illuminating than just yield, since berry size and fruit load determines the ultimate yield. Figure 9 shows the average relationship between berry size and the portion of full water use (applied water) from six vineyards in 1998 (from L.E. Williams 1998). Berry weight was 97% of maximum at 0.75 of full potential water use.

Figure 9. Relative berry weight vs. fraction of potential ET (applied water)



Fruit Quality

Visual estimates of fruit quality include the amount of sunburn, shrivel, and rot. Fruit quality can be assessed by measuring soluble solids (ºBrix), pH, titratable acidity (TA), and malic acid content. Each of these measurements along with the comments from the winemaker should be used to evaluate the success of any irrigation regime. Some wineries are also determining quality by color based on total phenolics, measured by gallic acid equivalent.

Important Considerations Using A RDI Strategy

Young Vines

Young vines should fully irrigated until the first bearing year to rapidly develop a strong root system and top in order to hasten vineyard development.

Use of Cover Crops

Vines in deep soil and high available water holding capacity soils located in a cool region may not reach the predetermined threshold by harvest or the threshold may be reached only after a sustained severe climate period. In these cases the soil/water resource is just too large for the environmental demand. The use of a cover crop to extract moisture might be appropriate to reduce the available soil water. In shallow soils or low water holding capacity soils, the threshold may be reached too early in the season causing water deficits in berry development Stage I. Water deficits at this time will cause smaller berries, which will reduce yields. To avoid this situation, irrigation can forestall the reaching the threshold until adequate shoot growth is attained

Rootstocks

Rootstock differences seem to be insignificant for the threshold selected; however, the rate at which the threshold is reached seems to be rootstock dependent. The more vigorous and root extensive rootstocks will be slower and more predictable in the increase in water stress as they approach the threshold. Less vigorous rootstocks and those that have a predominance of shallow roots will increase in water stress in a more rapid fashion especially when climatic conditions are harsher.

Low Vigor Vineyards

Low vigor vineyards regardless of the reason - nutrition, disease or pests - may develop a canopy with reduced leaf area, which may be insufficient to develop and mature the fruit. Water deficits are inappropriate in these cases.

Drought Periods or Low Rainfall Years

In years with low amounts of stored water at bud break, irrigation may be needed prior to bloom to attain adequate shoot growth. However, when vine vigor provides adequate to more than adequate canopy to support the crop load, limiting water availability and restricting or controlling additional canopy (leaf area) may be desirable.

Extreme Climate

In areas that experience severe climatic conditions for weeks at a time (Central Valley) excessive fruit exposure can raise the berry temperature preventing, the accumulation of pigments that result in poor berry color. Enhancement of color pigments (anthocyanin) and flavor compounds (phenolics) is a consistent result of optimum light exposure.

Leaf Removal

Water deficits can cause basal leaves to drop if the timing and severity is appropriate. Leaf removal, both mechanically or by hand, can open the canopy and supply additional light. These practices are synergistic and care should be exercised when using both practices—especially in more extreme climatic region of California.

Water Savings

Using a regulated deficit irrigation strategy, whether in response to drought conditions or in the normal course of producing quality fruit, considerable water can be saved over full potential vine water use. Typical water savings using RDI varies by growing region from 28 to 50% (Table 5).

Table 5. Irrigation Water Comparison Full/Deficit in Three Areas

	San Joaquin Valley	Lodi	North Coast
Full water use (in)	29	27	24
Soil storage (in)	4	9	10
Net irrigation requirement (in)	25	18	14
Irrigation efficiency (%)	90	90	90
Gross irrigation requirement (in)	27.8	20	15.6
Deficit irrigation use (in)	22	18	16
Soil storage (in)	4	9	10
Net irrigation requirement (in)	18	9	6
Irrigation efficiency (%)	90	90	90
Gross irrigation requirement (in)	20	10	6.7
Deficit/Full (%)	28	50	43

Water Use Efficiency
:
Water use efficiency can be viewed from the perspective of the amount of grapes per unit of applied water consumed or the total water consumed. Total water consumed (ETc) includes soil water contribution, effective in season rainfall, and irrigation. Regardless which measure of water use efficiency used, full potential vine water use is the least efficient (Table 6). An increase in efficiency is possible using deficit irrigation. RDI level 3 (most severe) was the highest water use efficiency while the less severe RDI level 2 was intermediate.

Table 6. Water Use Efficiency
2005 Syrah, Galt

Treatment	Yield lb /vine	Lbs Product / Acre Inch Water	
		Applied Water	Consumed Water
Full Potential	16.4	522	379
RDI Level 2	11.5	810	418
RDI Level 3	10.8	983	479

References:

Chalmers. D.J., G. Burge, P.H. Jerie, P.D. Mitchell. 1986. The mechanism of regulation of Bartlett pear fruit and vegetative growth by irrigation withholding and regulated deficit irrigation. Journal of the American Society of Horticultural Science 111, 904–907.

Chalmers, D.J., P.D. Mitchell, L. Vanheek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. Journal of the American Society of Horticultural Science 106, 307–312.

Coombe, B.G. 1960. Relationship of growth and development to changes in sugars, auxin and gibberellins in fruit of seeded and seedless varieties of Vitis vinifera. Plant Physiol. 35: 241-250.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods, Journal of Experimental Botany 2004 55(407):2427-2436

Kliewer, W.M. and N.K Dokoozlian. 2005. Am. J. Enol. Vitic. 56:2.

Lundquist, E.J., T.L. Prichard, R.J. Smith. 2005. Regulated Deficit Irrigation Effects on California North Coast Cabernet Sauvignon. Abstract presented to 56th Annual Meeting of the American Society for Enology and Viticulture.

Matthews, M.A. and M.M. Anderson. 1989. Reproductive development in grape (Vitis vinifera L.): responses to seasonal water deficits. Am J Enol Vitic 40(1):52–60

Mullins, M.G., A. Bouquet, E. Williams. 1992. Biology of the grapevine, published by Cambridge University Press.

Prichard, T.L., P.S.Verdegaal, and C.A. Ingels. 2009 Deficit Irrigation Management Strategies and the Influence of Extended Maturation on Vine Health, Fruit Yield and Quality: Syrah in Region III-IV. Report to California Department of Water Resources

Williams, L. E., D. W. Williams, and C. J. Phene. 1992. Modelling grapevine water use. Proc. 8th Aust. Wine Indust. Tech. Conf

Van Zyl, J.L. 1984. Response of colombar grapevines to irrigation as regards quality aspects and growth. South Afr. J. Enocl. Vitic. 5:19-28