TREE WATER REQUIREMENTS & REGULATED DEFICIT IRRIGATION

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The goal of irrigation scheduling is to supply the proper amount of water to the orchard on a timely basis. Good irrigation management insures that an adequate supply of soil moisture is maintained throughout the season. Informed irrigation decision making requires knowledge of the water use requirements of the trees and irrigation system performance, including the uniformity of application and delivery rates. Information on how productivity is affected by suboptimal irrigation practices also can be used to guide irrigation decision making. We believe that our studies on pistachio tree water use, response to season-long deficit irrigation, and regulated deficit irrigation provide growers with the agronomic information necessary to successfully manage irrigation, both in normal water years and in drought periods.

Pistachio trees have a reputation of being drought tolerant, for being able to survive and even produce modest crops with very little water. However, drought tolerance does not mean that pistachio trees require little water for optimal performance. Indeed, we have found that mature pistachio trees can utilize water at a fast rate; much faster than other fruit and nut trees. If pistachio trees are under-irrigated during stress-sensitive periods, important tree processes can be adversely affected. Thus, one must recognize that the well-known drought tolerance of pistachio refers to its ability to survive under severe water stress conditions; it doesn't mean that the trees will grow rapidly or have high productivity if they are poorly irrigated.

There are two fundamentally different approaches used today for scientific irrigation scheduling: 1) monitoring soil moisture levels by hand or with various instruments and replenishing soil water in a timely fashion, and 2) estimating how much water the crop is using and applying water to match this crop water requirement. This latter technique is known as the water budget and involves knowledge of the soil, plant and climate. An additional scheduling approach, now primarily in the research phase, uses plant-based measurements of water status or some parameter that is related to water status. These measurements are made with specialized equipment, such as the pressure chamber, to signal when irrigation is needed.

This chapter will focus on the water budget approach which we believe is the most cost effective, comprehensive water management technique currently in use. Successful utilization of the water budget enables us to answer the two questions necessary for effective irrigation: 1) when to irrigate, and 2) how much water to apply. While most of California's pistachio orchards are drip or microsprinkler irrigated, we also cover water budget approach issues in this chapter that relate primarily to surface irrigation (border strip and furrow). These include soil water holding capacity, allowable depletion, and rooting depth.

THE WATER BUDGET

Since the orchard water budget is essentially an exercise in balancing water additions and losses from the orchard, the irrigation requirement is the difference between the water losses and effective rainfall. Thus,

Irrigation requirement =
ETc - Effective rainfall + Irrigation system losses.

Crop evapotranspiration (ETc) is the sum of evaporation from the soil (E) and transpiration from leaves (T). Effective rainfall is the total rainfall amount stored in the profile; an amount which can be difficult to estimate. Rainfall, however, can supply a significant part of the seasonal crop needs in some areas of California and, therefore, should not be ignored. While the amount of rainfall stored in the soil depends on its intensity and duration,

experience has shown that this value usually ranges between 50 and 70 percent of total winter rainfall. Rather than use estimates, the best way to evaluate effective rainfall is to measure the depth of wetted soil at the beginning of the season. As for losses other than ETc, deep percolation of water below the root zone and surface runoff can occur when using flood, furrow, basin or border irrigation, even with the best management. While this waste can be minimized, it is usually not economically feasible to eliminate these losses entirely.

The water budget procedure for drip and low-volume sprinkler-irrigated orchards allows you to use information on ETc, rainfall and irrigation system losses to determine your irrigation program. For surface irrigated orchards, you need additional information on soil water holding capacity, root zone depth, and allowable depletion levels to schedule irrigations. These data allow you to estimate the size of the soil water reservoir, and by knowing the rate that water is being used, you can determine when to irrigate next and how much water will be needed to refill the reservoir. Figure 13a illustrates this analogy, but it should be emphasized that storing soil water is not as simple as holding water in a reservoir. The problems of replenishing the root zone profile and the ability of trees to extract stored water will be discussed later.

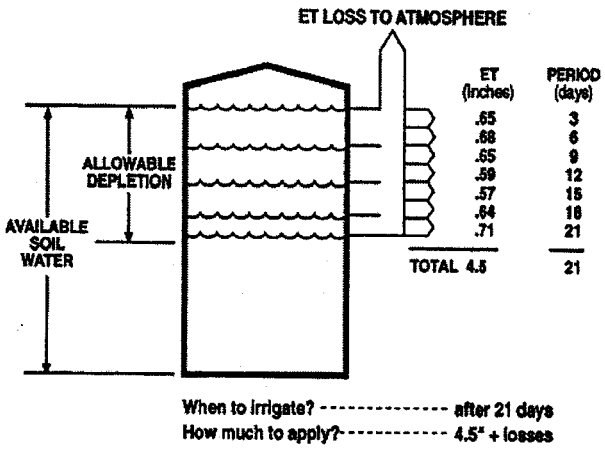

Figure 13a. Analogy of irrigation scheduling using the water budget approach to replacement of water in a tank.

INFILTRATION

Water applied to a field infiltrates into the soil quickly at first and then slows down as irrigation continues. With surface irrigation methods (flood, furrow, border), the *soil infiltration rate* controls the amount of water that infiltrates and, therefore, may dictate the length of time you should irrigate. With sprinklers or localized irrigation (drip, low-volume sprinklers), the *application rate* determines the amount of water infiltration, assuming the minimum soil intake rate is not exceeded. Because the goal of efficient surface irrigation is to store a specific quantity of water in the soil, the infiltration rate is of fundamental importance with surface methods. These intake rates are greatest early in the season and usually decrease with each successive irrigation. While reasons for this are not well understood, it seems to be associated with changes in soil surface chemistry and structure. It can make the irrigator's task much more difficult and will be discussed later.

As water is applied to a field with surface irrigation methods, it almost completely fills the pore space in the profile's upper level. As irrigation continues, the depth of the zone at or near saturation increases. If the soil profile has been dry, a distinct boundary exists between wet and dry soil. When irrigation stops, some water moves out of the wetted zone and partially wets the dry soil below it. If the subsoil is already moist, the water passes below the root zone, and is not available for tree uptake.

Soil is a complex matrix composed of solid particles, void space and small amounts of organic material. Its water-holding capacity depends on the relative volume of void space (porosity) and the size of the pores. There is a direct relationship between soil particle size (texture) and pore space. Coarse textured soils (sands) have a smaller percentage of *total pore space*, and fine textured soils (clays and clay loams) have a greater percentage. On the other hand, even though clays have a larger porosity, average *pore size* is small compared with sands; thus, water moves much more readily in sandy soils.

After irrigation, soil water drains rapidly at first. As the large pores empty, the soil conducts water much less readily. After 3 or 4 days, the rate of water movement slows and can be

neglected for our purposes. At this point, the remainder of the soil water can be considered stored. The water content of the soil at this point is called field capacity (FC) and is the upper limit of water storage. A practical lower limit of soil water content below which crop growth is severely reduced by water stress has been defined as the permanent wilting point (PWP). Although pistachio trees do not visibly wilt, the PWP is as significant for them as for plants that show wilting.

The difference between FC and PWP is termed the available water content (AWC). Table 1 shows the range and average AWC of various soil types in units of inches of water per foot of soil. While several terms are used to express soil water contents, inches of water per foot of soil is a practical unit and can be visualized as the depth of water obtained if all available water were extracted from a one-foot depth of soil. As shown in Table 1, sands, with their relatively small total pore space, do not store large amounts of water. What water is held is easily removed by plant roots. Clay soils, because of their large total pore space, have a large AWC. However, their small water-filled pores have attractive forces that tend to resist water extraction by plants. Intermediate textured soils, the loams, have good water-holding properties, and because of their wide range of particle sizes, are readily able to release their water for plant use. Once the AWC is known, the total water-holding capacity of the profile is easily determined by multiplying the AWC by the depth of the root zone.

Table 1. Estimates of available water content for different soil types.

	Available water content	
Soil type	Range (in/ft)	Average (in/ft)
Coarse textured sand	0.50 - 1.25	0.90
Sandy loams	1.25 - 1.75	1.50
Silty clay loams	1.50 - 2.30	1.90
Clay	1.60 - 2.50	2.10

The wide range of AWC for each soil type demonstrates the uncertainty of estimates and also indicates that factors other than particle size affect water holding capacity. The University of California Cooperative Extension and the USDA Natural Resources Conservation Service have developed specific AWC information for many areas of California. This information can be obtained from the local offices of each organization. Precise determinations of AWC are generally not necessary for irrigation scheduling. Indeed, the expressions FC, PWP and AWC are actually concepts and should not be thought of as absolute, fixed amounts; they are practical estimates used to represent what are actually continuously changing water contents in the profile.

ALLOWABLE DEPLETION

While it is useful to compare soil water storage with a reservoir, it is not entirely accurate. As soil water content decreases, it becomes more difficult for roots to extract the remaining water, even though it is well above the PWP. This is because after the large soil pores give up their water, the smaller pores must assume two important functions: 1) to store water, and 2) to conduct water moving between the soil and plant roots. Small pores not only hold water tightly, but water travels exceedingly slowly through small pores. These factors combine to limit water uptake as soils dry out. Thus, crop growth decreases before the entire root zone reaches the PWP. For this reason, you should usually irrigate before the root zone water content reaches a level that restricts growth below its maximum potential.

Unfortunately, no single soil water level can be recommended for all situations. The safe amount of depletion [called allowable depletion (AD) or yield threshold depletion (YTD) and usually referred to as a percentage of the total available water in the root zone] depends on numerous factors, including rooting density, soil texture, and the weather. Figure13b illustrates the relationship between AD and plant growth for two extreme situations. One example is a low root density crop on a clay soil grown under hot, windy conditions. Here a depletion of more than 30 to 40 percent of the available root zone moisture may affect crop growth. On the other hand, a densely rooted crop grown on a sandy soil under mild conditions may be able to tolerate an AD of 70 to 80 percent before growth rate

drops. Allowable depletion determination is, therefore, not easily made, but precise estimates are not required. The particular sensitivity to water stress during bloom, rapid shell and kernel development, and shoot initiation and growth periods suggests irrigating pistachio trees at relatively small depletion levels during these periods. At other times, 50 to 75 percent depletion has been used successfully in California orchards.

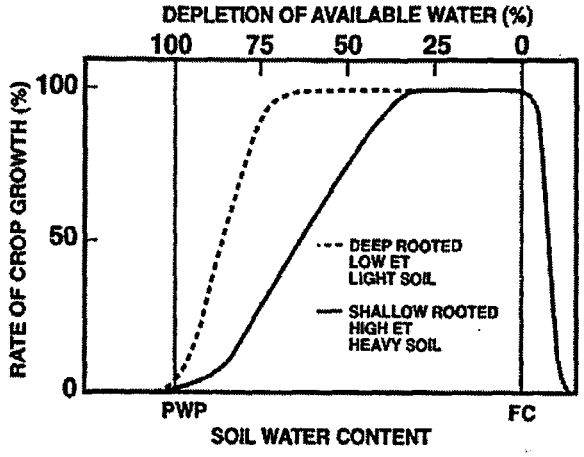

Figure 13b. Relationship between allowable depletion of soil water and plant growth for two extreme situations.

Remember: The objective of irrigation is to keep adequate moisture in the soil. Estimates of allowable depletion allow use of the maximum amount of soil water (consistent with optimal tree performance) between irrigations. This approach means growers can irrigate the fewest times possible and, because there are fixed costs associated with each irrigation, this is usually the most economical practice. For example, if 50 percent of the total AWC can be safely removed by the trees between irrigations, irrigating when only 25 percent of the available water in the root zone has been depleted will require twice as many irrigations. *The AD concept is important only for surface irrigation and sprinklers; it is irrelevant for drip and microsprinklers.* Indeed, the goal of these high frequency systems is to maintain soil moisture levels relatively constant over the season as opposed to conventional methods that involve wetting and drying cycles.

WATER REQUIREMENTS AND METHODS OF ESTIMATING ETc

The water budget procedure can be used successfully only if the ETc rate is known. ETc depends on climatic, plant, soil and orchard management factors, each of which will be briefly discussed.

Weather conditions

Weather conditions largely determine ETc rates. Because both processes that make up ETc involve vaporizing water, the energy status of the atmosphere is of primary importance. Components of the energy balance include solar radiation (sunlight intensity), air temperature, humidity and wind speed. Additionally, if an orchard is bordered upwind by bare ground, advective energy can cause ETc rates to increase drastically and must be taken into account in estimating crop water use.

Evaporation

Evaporation is important only when the soil surface is wet. After an irrigation, water evaporates from the soil at the same rate that trees transpire. As the soil surface dries out, upward water flow is drastically reduced, and surface evaporation decreases rapidly. Thus, the total amount of water evaporated depends on the area of the orchard floor that is wetted and the number of irrigations. Because both evaporation and transpiration require energy, speculation has focused on whether excessive evaporation will reduce the available energy and thus lower the crop's transpiration rate. The answer is unclear, although it is certain that evaporation does not reduce transpiration on a one-to-one basis.

Plant factor

The most significant *plant factor* affecting ETc is the size of the total leaf area intercepting solar radiation. Thus, the size of the tree canopy, the tree spacing and the stage of leaf development during the season all influence crop water use. Rather than trying to measure leaf area, research indicates that the degree of plant cover (shade) of the orchard floor correlates well with sunlit leaf area. The relationship between plant cover and ETc is important in determining irrigation schedules for young orchards. Field studies show

that ETc reaches its maximum when 50-60 percent of the ground is shaded by tree canopies at midday. Figure 13c shows the relationship between percent ground cover and ETc for almonds. The relationship for pistachio trees has not been established, but since the canopy architectures are similar, the almond research is most likely applicable to pistachio trees. Note that in Figure 13c the relationship between percent shade and ETc varies considerably from a one-to-one basis. Presumably, the area of the orchard floor receiving direct sunlight transfers energy to the tree canopies by microadvection, thereby increasing the ETc rate.

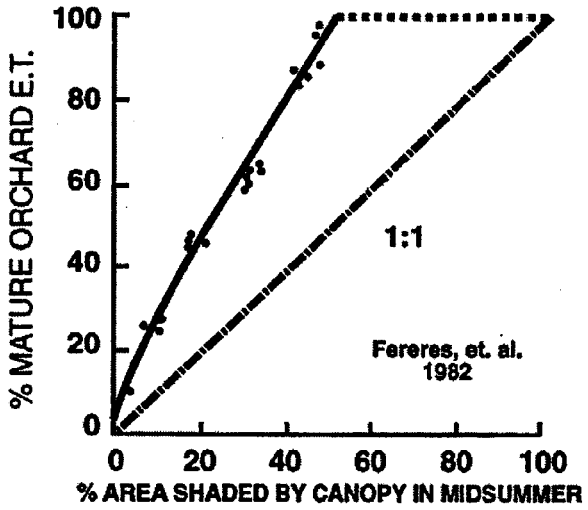

Figure 13c. Relationship for developing pistachio trees between ET and percent shaded area of the orchard floor.

While most factors affecting ETc cannot be manipulated by growers, irrigation system and orchard floor management can influence water usage. As noted earlier, the frequency of irrigation and size of the wetted surface area influence evaporation. With good management, the irrigator can control both factors and limit evaporation loss. With furrow irrigation of young orchards, one furrow can be used on either side of the tree rows rather than completely wetting the ground with multiple furrows. Studies have shown that localized irrigation, including drip, can significantly decrease the amount of evaporation and, therefore, save water in young orchards. In mature orchards, little, if any, reduction of surface evaporation is achieved by using localized irrigation methods.

Although cover crops can have many benefits, an undesirable consequence is that they use considerable amounts of water. Cover crops or uncontrolled weeds can increase seasonal orchard ETc by 20-25 percent in deciduous orchards and by much more in young trees. Therefore, the cost and availability of water should be taken into account when considering cover crops.

Since climatic conditions have the greatest influence on ETc, many mathematical formulas have been developed to estimate ETc based on meteorological measurements. Reference crop ETc (ETo) values are derived from these empirical equations, ETo values approximating evapotranspiration from a closely cut grass crop. Another index of evaporative demand is evaporation from a free water surface (Epan). But since pan evaporation is strictly a physical mechanism and transpiration is biologically controlled by the leaf stomata, ETo has been shown to correlate better with actual crop ETc than Epan. Therefore, crop water use estimates made with ETo values are potentially more accurate. Long-term, historical average daily ETo has been compiled for all locations in California and is available in UC Publication #21454 ("Irrigation Scheduling--A Guide for Efficient On-Farm Water Management). Bi-monthly ETo values for Parlier are shown in Table 2.

Table 2. Long-term, historical average ETc for mature pistachio trees under clean cultivation in San Joaquin Valley, CA

Date	ETo (in)	Kc[1]	ETc (in/period)	ETc (in/day)	ETc (gal/tree/day)[2]
Apr 1-15	0.16	0.07	0.17	0.011	2.0
Apr 16-30	0.18	0.43	1.16	0.077	13.8
May 1-15	0.21	0.68	2.14	0.143	25.7
May 16-31	0.24	0.93	3.57	0.223	40.1
Jun 1-15	0.25	1.09	4.09	0.273	49.1
Jun 16-30	0.26	1.17	4.56	0.304	54.6
Jul 1-15	0.27	1.19	4.82	0.321	57.7
Jul 16-31	0.26	1.19	4.95	0.309	55.5
Aug 1-15	0.24	1.19	4.28	0.285	51.2
Aug 16-31	0.22	1.12	3.94	0.246	44.2
Sep 1-15	0.19	0.99	2.82	0.188	33.8
Sep 16-30	0.16	0.87	2.09	0.139	25.0
Oct 1-15	0.12	0.67	1.21	0.081	14.6
Oct 16-31	0.09	0.50	0.72	0.045	8.1
Nov 1-15	0.06	0.35	0.32	0.021	3.8
TOTAL			40.80		

[1] Crop coefficient for grass reference crop (Eto). ETc = (Kc)(ETo)

[2] Based on 17 x 17 ft tree spacing. The following equation can be used to calculate individual tree ETc for other spacings: gal/tree/day = ETc(in/day) x spacing(ft^2) x .622(gal/in.ft^2)

The relationship between ETc and ETo, when expressed as a ratio (ETc/ETo) is called the crop coefficient (Kc). The Kc varies with the crop and its stage of growth, but it is assumed to be independent of location for most areas in California. Thus, we believe that a single set of pistachio tree Kc values can be used throughout the state, with the exception of coastal areas.

Table 2 gives ETc estimates on a bi-monthly basis for pistachio trees grown in the San Joaquin Valley under clean cultivated conditions during a normal weather year. ETc was determined based on long-term ETo and research-generated Kc values (also shown in Table 2) assuming: ETc = (Kc) (Eto) and is shown as inches per each bimonthly period, inches per day, and gallons per tree per day assuming a 17 x 17 ft tree spacing. Note that the peak pistachio ETc rate (early July through mid- August) is approximately 0.32 inches per day, which is significantly greater than published values for other deciduous trees. For example, peak almond ETc in the San Joaquin Valley is approximately 0.25 inches per day. This high pistachio ETc is reflected by a peak Kc of 1.19 vs. 0.96 for almond. In other words, pistachio trees can use water at a rate 19% greater than a well-watered grass crop, while almonds use 4% less.

Long-term average ETc data can be successfully used for irrigation scheduling even though a normal year seldom occurs. Common sense should be used to modify irrigation schedules based on long-term averages, if the season has drastically higher or lower temperatures or winds than normal. If you want to be more accurate, current (real time) ETo estimates are calculated from data collected from the CIMIS network of automated weather stations, and this data is available from the State of California Department of Water Resources. Also, several newspapers and radio stations in California report reference crop data. You must be careful to recognize whether the data are estimates of Epan, ETo, or some other reference value, in that they each represent different measurements, and the appropriate set of crop coefficients must be used to avoid errors.

The CIMIS network can be accessed through the Internet (www.cimis.water.ca.gov). For further information on the CIMIS network, contact:

State of California, Department of Water Resources
Water Use Efficiency Office
901 P Street, Third Floor
P.O. Box 942836
Sacramento, CA 94236-0001

IRRIGATION EFFICIENCY

The information discussed so far can be used to estimate when to irrigate and the amount of water needed to refill the soil water reservoir (net irrigation requirement). When water is applied to an orchard, however, some losses are unavoidable, especially with surface irrigation methods, and they must be considered in calculating the actual amount of water to be applied (gross irrigation requirement). The type of irrigation used, soil and climatic conditions, and water management practices largely determine irrigation efficiency.

Water applied to a field can be lost by runoff, percolation below the root zone, evaporation and, with sprinklers, spray evaporation and drift. The goal of good on-farm water management is to minimize these losses. For instance, runoff can be minimized by using an irrigation system design that prevents it or reuses the collected tailwater. Application efficiency (Ea) is a term commonly used to describe how well growers irrigate. It is defined as the percentage of applied irrigation water that is available for crop use.

$$Ea = \frac{\text{Water used by plant}}{\text{Water applied}}$$

In general, Ea is directly related to how uniformly water can be applied over the surface. Therefore, the method of irrigation is of prime importance.

Most pistachio orchards use drip and microsprinkler irrigation, rather than the surface methods (basin, furrow and border strip) commonly used with other deciduous trees. Each method differs in how uniformly water can be applied. With surface irrigation, the intake properties of the soil and the rate that water moves over the field determines the uniformity of infiltration. The faster the water moves to the bottom of a basin or run, the smaller the difference in the opportunity time for infiltration between the top and bottom of the field. Distribution of water under sprinkler irrigation depends mostly on systems, design, including spacing, nozzle type and size, riser height, and operating pressure. With drip and microsprinklers, design and maintenance determine the uniformity of application. In general, sprinkler and drip/microsprinkler systems can be operated with higher efficiencies than surface methods, since soil intake properties are of minor importance. Moreover, estimating application efficiency with these systems is much easier than with surface methods.

Because application efficiencies vary, each situation must be evaluated for Ea. Cooperative Extension, the Natural Resources Conservation Service, and private consultants offer assistance in evaluating systems. The following list shows gross estimates of Ea associated with different irrigation methods.

System	Ea (%)
Basin	70-80
Border strip	70-80
Furrow	65-75
Sprinkler	75-85
Drip, microsprinkler	85-95

DEVELOPING IRRIGATION SCHEDULES

Each component of the water budget approach has been discussed; it is a simple procedure to determine an actual irrigation schedule. For surface irrigated orchards, this means the water loss through ETc is totaled until it exceeds a predetermined percentage of the total available water in the tree root zone. At that time, you need to irrigate and should apply the amount equal to the ETc loss plus the unavoidable loss associated with each irrigation. For drip/microsprinkler irrigated orchards, you must decide upon an irrigation frequency and then apply water to meet ETc and system losses due to application nonuniformity. The following examples using long-term, historical ETo show actual development of irrigation schedules for a mature pistachio orchard; first for a microsprinkler system, and then for a border strip system.

General Information

Location: San Joaquin Valley, California
Soil: Sandy loam
Rooting depth: 6 ft
Tree spacing: 17 x 17 ft
Available water storage capacity (AWC): 1.5 in/ft
Allowable depletion: 50% of total AWC

EXAMPLE 1.
Microsprinkler irrigation system.

Assume:
application efficiency: 90%
application rate: 11 gallons/sprinkler/hour (one sprinkler per tree)
irrigation frequency: every 3 days

Step 1. Calculate the water use rate (July 1-15, for example)

Orchard Etc
= (Kc)(ETo)
= (1.19)(0.27 inches/day)
= 0.32 inches/day

Individual tree ETc
= (orchard ETc) (tree spacing) (conversion factor)
= (0.32 inches/day) (17 x 17 ft) (.622 gal/in.ft^2)
= 58 gal/tree/day

Step 2. Calculate the irrigation amount.

$$\text{amount to apply} = \frac{\text{Etc}}{\text{application efficiency}}$$

$$= \frac{58 \text{ gal/tree/day}}{0.90}$$

= 64 gal/tree/day
= 193 gals every 3 days

Step 3. Calculate the set time (duration of water application).

$$\text{Set time} = \frac{\text{Amount to apply}}{\text{application rate}}$$

$$= \frac{193 \text{ gals}}{11 \text{ gals/hr}}$$

= 17.5 hrs every 3 days

EXAMPLE 2.
Border strip irrigation system.

Assume:
system delivery: 500 gallons/minute/acre
application efficiency: 80%

Step 1. Estimate available moisture in the root zone.

Total available water (AW) = AW x rooting depth
= (1.5 in/ft) (6 ft)
= 9.0 inches

Step 2. Calculate the amount of depletion allowed between irrigations.

allowable depletion (AD) = (total AW)
(depletion %)
= (9.0 inches) (0.50)
= 4.5 inches

Step 3. Estimate normal orchard water use.

Historical ETc data from Table 2 for a clean cultivated orchard are plotted as cumulative ETc vs. time in Figure 4.

Step 4. Decide when to irrigate.

Assuming that the soil water profile is full as the season begins (from a combination of winter rainfall and postharvest irrigation), deciding when to irrigate is simply a matter of periodically determining when the cumulative ETc equals the amount of depletion allowed (from Step 2). This procedure is illustrated in Figure 4 and results in a total of 9 irrigations, beginning on May 20, then June 8 and so on.

NOTE: If the root zone is only partially wet at the beginning of the season, the initial total available stored water can be estimated by soil probing.

Step 5. Calculate the irrigation amount.

$$\text{Amount of apply} = \frac{\text{Depletion amount}}{\text{Application efficiency}}$$

$$= \frac{4.5 \text{ inches}}{0.80}$$

$$= 5.6 \text{ inches} \times 27{,}100 \text{ gal/acre-inch}$$

$$= 152{,}000 \text{ gals/acre}$$

Step 6. Calculate the set time.

$$\text{Set time} = \frac{\text{amount to apply}}{\text{delivery rate}}$$

$$= \frac{152{,}000 \text{ gals/acre}}{500 \text{ gals/min}}$$

$$= 300 \text{ mins/acre}$$

$$= 5 \text{ hrs/acre}$$

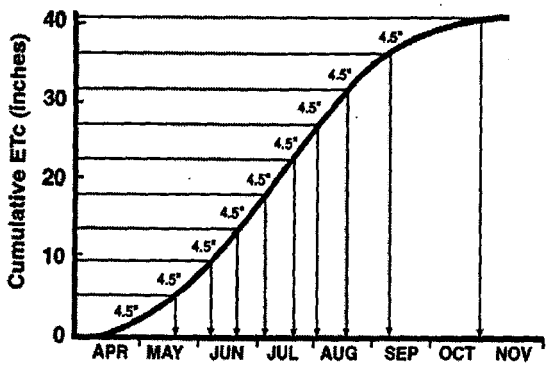

Figure 13d. Graphical means of estimating irrigation dates using the water budget approach and assuming long-term, historical ET.

VERIFICATION OF THE WATER BUDGET

The water budget procedure is based on sound agronomic principles. However, even if the most accurate information is used, it is a good idea to check soil moisture levels periodically. This can be done with a soil probe or auger based on how the soil sample behaves when squeezed in the hand. Or, soil-based instruments can be used. This monitoring is necessary because of the uncertainties in the water budget associated with 1) the amount of water applied and the depth of penetration, 2) estimating AWC and AD due to spatial variability of soils, and 3) estimating application efficiency.

ADDITIONAL CONSIDERATIONS

Season-long deficit irrigation

To evaluate the consequences of not supplying mature trees with all the water they could use, we conducted a three-year study where various percentages of full ETc (0, 25, 50, 75 and 100%) were applied uniformly over the season. Frequent and intensive measurements of all important tree performance parameters were made. Please refer to our paper in the 1987 California Pistachio Industry Annual Report for detailed results (www.pistachios.org).

We found that virtually all tree processes or performance parameters were affected by water stress. The magnitude of the response depended on the process/parameter and the intensity of the stress. To illustrate the effects, we've ranked the important tree processes or parameters in Figure 13e based on their sensitivity to the range of water stress imposed in our study. The response bars were generated using average tree response values over the second and third years of stress *relative to 100% ETc*. Note the sensitivity ranking of the important yield components (most stress sensitive listed first): blanking and nut abortion > shell splitting > nuts per tree > harvestability > individual nut weight and size. Marketable *yield*, the integrator of all the yield components, was more affected by the range of deficit irrigation levels imposed than any of the *individual* yield components.

Regulated deficit irrigation

The bulk of California's pistachio orchards are in high water cost areas; commonly $100/acre-ft. In a drought year, not only is water expensive, but it simply may not be available. Regulated deficit irrigation (RDI) is a technique that purposely stresses trees during certain stages of tree/fruit growth in order to reduce ETc (save water) while minimizing or eliminating negative impacts of stress on fruit yield or quality. This approach differs from season-long stress in that the deficit irrigation is restricted to stress-tolerant periods. First applied on stone fruit in Australia and New Zealand, successful RDI depends primarily on inducing stress during periods of slow vegetative and reproductive growth. We began testing the RDI concept for pistachios in 1989 and proposed two stress-tolerant periods: 1) from mid-May through early July (growth stage 2), just after full shell development and before the onset of rapid kernel growth; and 2) postharvest.

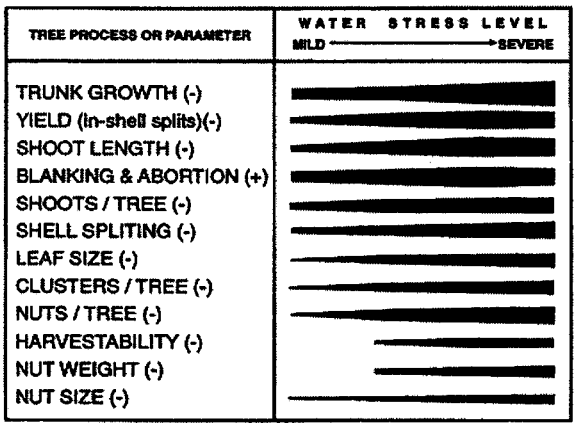

Figure 13e. Generalized diagram of the sensitivity to water stress of selected pistachio plant processes and parameters. Widths of the horizontal bars at given stress levels represent the relative magnitude of the response and were developed by evaluating effects under dry land, 25, 50, 75% ETc relative to 100% ET (dry land illustrated as "severe" stress and 75% ET shown as "mild").

Stage 2 is our stress focus since it is after the initial shoot growth flush, when there is minimal nut growth (Figure 13f); the primary nut growth process during this period is shell wall thickening (lignification), and potential water use is increasing. A typical irrigation schedule for the proposed conservative RDI regime is shown in Table 3.

We conducted a large-scale, four-year project (1998-92) which evaluated numerous stress levels during the abovementioned periods in a deep-rooted orchard. We concluded that irrigating at 25-50% of potential ETc during stage 2 and postharvest did not affect production. Stress during stage 3 (early July through harvest) should be avoided.

Table 3. San Joaquin Valley pistachio water use (Etc) for normal and proposed RDI regimes. Irrigation schedule early in the season must take into account stored winter rainfall.

Growth Stage	Approximate phenology	Period	Reference water use <Eto> (inches)	Crop coeff. <Kc>	Normal Etc in period (inches)	Proposed RDI level (%)	Proposed RDI Etc (inches)
	Bloom	Apr 1-15	2.36	0.07	0.17	100	0.17
Stage 1	Leafout	Apr 16-30	2.36	0.43	1.01	100	1.01
	Shell Expansion	May 1-15	3.19	0.68	2.17	100	2.17
	Shell Hardening	May 16-31	3.40	0.93	3.16	50	1.58
Stage 2	Shell Hardening	Jun 1-15	3.84	1.09	4.19	50	2.09
	Shell Hardening	Jun 16-30	3.84	1.17	4.49	50	2.25
	Nut Filling	Jul 1-15	4.13	1.19	4.92	100	4.92
	Nut Filling	Jul 16-31	4.41	1.19	5.25	100	5.25
Stage 3	Nuf Fill./Shell Split.	Aug 1-15	3.54	1.19	4.21	100	4.21
	Shell Splitting	Aug 16-31	3.78	1.12	4.23	100	4.23
	Hull Slip	Sept 1-15	2.66	0.99	2.63	100	2.63
	Harvest	Sept 16-30	2.66	0.87	2.31	25	0.58
	Postharvest	Oct 1-15	1.71	0.67	1.15	25	0.29
Postharvest	Postharvest	Oct 16-31	1.83	0.50	0.91	25	0.23
	Postharvest	Nov 1-15	0.80	0.35	0.28	25	0.07
		Totals			**41.10**		**31.70**

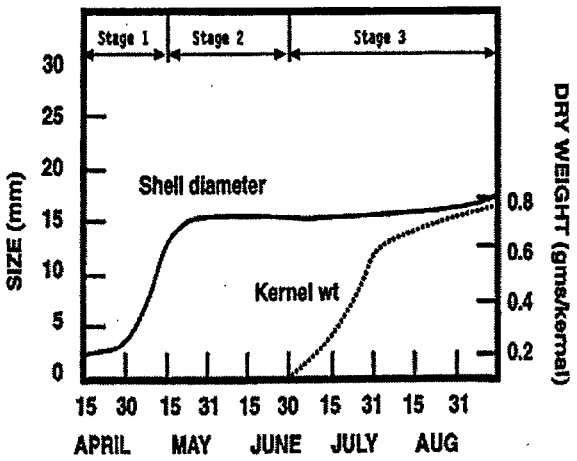

Figure 13f. Generalized time course development of shell and kernel growth for San Joaquin Valley pistachios.

Production scale tests have been conducted since 1992 with cooperating growers under a variety of soil conditions. Production scale sites have replicated irrigation regimes, are monitored as intensively as research plots, but allow for commercial evaluation of nut yield and quality. We have observed no negative effects of irrigating at 50% ETc during stage 2 or postharvest. Shell staining due to fungal disease also is occasionally lower apparently due to lower orchard humidity during the imposition of deficit irrigation.

In some cases, significantly higher shell splitting occurred with deficit irrigation during stage 1 (leafout through mid May). We attribute this to mild stress slightly reducing shell size and/or thickness. We believe that this can be due to the combination of a weaker shell and the developing kernel exerting additional physical pressure at the shell suture line. On the other hand, stage 1 stress can result in slightly smaller nuts at harvest. Ongoing research with both Atlantica and PGI rootstocks confirms that improved shell splitting, albeit with slightly smaller nuts, can be achieved with Stage 1 stress. This new work suggests that filled closed shell can be reduced by about 50% with stage 1 stress while nut size is reduced by 4 to 8%. Thus, if growers have relatively high closed shell at harvest, Stage 1 stress could be a tool to improve yield of marketable product. On the other hand, growers with no closed shell problem may not want to sacrifice fruit size for a small increase in split nuts.

There are other impacts of Stage 1 stress on pistachio production. Early season stress has been shown to cause unwanted premature shell splitting in mid stage 3. These nuts are subject to fungal disease and possible aflatoxin-affected nuts at harvest. Additionally, processor data shows that loose shells and kernels are higher with Stage 1 stress. On the positive side, we found that Stage 1 stress with PG1 in an "on" alternate bearing year significantly increased fruit load in the following "off" year, suggesting that this RDI strategy may be useful in mitigating alternating bearing.

We must also point out that irrigating at 25% ETc during stage 2 on a very shallow soil reduced both shell size and splitting. Where there is a small soil moisture reservoir, we recommend irrigating at 50% ETc during stage 2. With deeper root zones and consequently larger soil moisture levels at the onset of stage 2, 50% ETc during the deficit irrigation period is conservative.

RDI appears to be a promising technique to save water while maintaining or even enhancing production of marketable product. The key is being able to impose the desired stress at the correct time. The deeper the soil and the greater the soil moisture reserves going into stage 2, the longer the lag between cutting back on irrigation and the onset of tree stress. RDI is much easier to impose with drip/microsprinkler irrigation which fortunately is used on an estimated 85% of the pistachio acreage.

Young trees

Estimating the irrigation requirements of immature pistachio trees is difficult for two reasons. First, researchers have yet to develop specific information on young pistachio ETc. We must assume that information from other deciduous trees, such as that for almonds presented in Figure 13c, applies to pistachios. Successful application of experimental results also depends on accounting for differences in irrigation regimes. Since the evaporation component accounts for a much larger percentage of ETc in young orchards, differences in wetted

surface area and frequency will have relatively large effects on ETc.

The second problem in determining the irrigation requirements of first- or second-year trees is that application efficiency of the irrigation systems cannot be measured easily. This is because of the small size and uncertain location of the root zone. Since irrigation systems are usually designed to perform optimally in a mature orchard, a significant amount of water can be lost to deep percolation in young orchards just because water is applied outside of the root zone. Even drip/microsprinkler systems that have high distribution uniformities and high application efficiencies in mature orchards have much lower application efficiencies in new plantings (values of 30 to 50 percent are typical in first-year trees). Application efficiencies improve as the root zones develop.

Growers can maximize the application efficiency in young orchards by managing their irrigation systems to limit the amount of water applied outside the root zone. With a drip/microsprinkler system, you can place the emitters close to the trunk, recognizing that they will be moved as the trees mature. Another alternative is to operate microsprinklers at reduced pressures to decrease the area wetted, although you should check the system to make sure it maintains a high uniformity of application. With surface systems, small furrows on either side of the tree can improve application efficiency.

Irrigation-disease interactions

Water management can influence the predisposition of pistachio trees to infection by *V. dahliae*. Since soil temperature might be a factor influencing infection, early season irrigation timing may have to be adjusted in orchards with *Verticillium*. The experience of cotton growers facing this problem can be used as a guide to develop optimal irrigation strategies. For pistachios, refill the soil profile with a winter irrigation, and delay the first post-leafout irrigation as long as possible. This practice allows the soil temperature to remain relatively high during the spring, a time when most *Verticillium* infections occur. It should be noted that withholding water for too long a period can create tree water deficits that may ultimately affect orchard yield more than the disease.

Fungal diseases, primarily Alternaria, can reduce fruit quality due to shell staining. In orchards that have slowly permeable soils and applied water ponds on the soil surface for days after an irrigation, or where sprinkler spray patterns are directed into the tree canopies, fungal disease is more prevalent. Higher humidity levels in such orchards promote disease activity. With sprinklers, the best solution is to use low-angle sprinklers. With poor infiltration rate soils, we have shown that buried drip irrigation can reduce orchard humidity, thus reducing incidence of fungal diseases. The key is installing the system such that the soil surface is not (or is minimally) wetted throughout the season.

Poor infiltration or fixed surface water deliveries

In addition to fungal disease, standing water can cause poor root health and can be a logistical nightmare. Many growers do not want water standing in their orchards for more than 24 hours. Because the soil intake rate dictates the quantity of water entering the soil with surface irrigation, the amount that infiltrates in 24 hours is the maximum application for each irrigation in these situations. On low infiltration rate soils, this may be less than the net irrigation requirement calculated by the water budget. For the example presented earlier, assume that the infiltration rate averages 0.10 inch per hour. Thus, approximately 2.4 inches of water infiltrate at each irrigation. This value becomes the amount of depletion allowed, rather than the 4.5 inches we calculated, based on AWC, AD and rooting depth. This means the grower will have to irrigate more frequently than originally scheduled but with less water per application.

Similarly, the irrigation schedule can be adjusted, if water deliveries from the irrigation district occur on a fixed schedule. For example, if water is received every two weeks, the irrigator simply determines the crop water usage over the last two-week period and applies that amount plus losses due to system inefficiency. So rather than applying the same amount of water per irrigation, the quantity applied will change throughout the season.

Consultants

The use of irrigation consultants represents a viable option for growers interested in improved water management. Growers commonly hire consultants to provide information and/or make decisions for cultural practices where the grower lacks knowledge, time, and/or recognizes the disastrous consequences of poor decisions. While all the information necessary to develop water budget-based irrigation schedules is readily available, the "housekeeping" aspects of irrigation scheduling can be time-consuming, making the use of personnel specializing in this discipline desirable.

PISTACHIO PRODUCTION MANUAL

FOURTH EDITION

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Pistachio Production Manual

Fourth Edition • 2005

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