



Irrigation and Nitrogen Management

This publication addresses the nexus between irrigation and nitrogen (N) management in California agriculture with a focus on fundamental irrigation management practices capable of protecting groundwater quality in California.

Irrigation Is Essential

Irrigation and rainfall supply crop water needs and support crop development. In most regions of California, rainfall is insufficient to meet crop water needs, and irrigation is required to optimize production. When water supply does not meet crop water requirements, water stress occurs, resulting in closure of leaf stomata, reduced transpiration (loss of water vapor from leaves), and reduced photosynthesis, which usually impacts yield. In most irrigated cropping systems, water stress is a major reason for reduced productivity and crop quality. Therefore, irrigating effectively is a fundamental agronomic concern for growers. In addition to supplying water for crop transpiration, irrigation is beneficial for leaching salt that may accumulate in the root zone of a crop and for affecting the microclimate, such as for protection during freezes.

Too Much Irrigation

Irrigation beyond what the crop uses for transpiration and photosynthesis or what may be needed for salinity or frost control often has little or no benefit to crop production. Too much irrigation or inefficient irrigation may compromise productivity or waste resources. An example is timely application of N fertilizer at the proper rate and placement within the crop root zone. If N fertilization is followed by irrigation that is excessive, too long in duration, or has poor application uniformity, the N fertilizer may be leached out of the root zone, resulting in N deficiency that reduces crop

**ALLAN FULTON AND
DANIEL S. MUNK**
University of California
Cooperative Extension

productivity and quality. Adding more fertilizer to correct the deficiency after the fact may not prevent a loss in crop productivity, but it will increase the risk of leaching nitrate while escalating production costs.

Nitrates are water soluble and do not adhere to soil, so they may leach during irrigation. How readily nitrates move within and through the soil depends on the soil porosity, soil moisture gradients within the soil profile, and gravitational forces. When too much irrigation is applied, nitrate is at more risk to percolate below the crop root zone and deeper into groundwater aquifers. The high solubility and mobility of the nitrate molecule in irrigated farming systems is the chief reason why it is a challenge to manage irrigation effectively while protecting California's surface and groundwater systems.

Impacts of Poor Irrigation and Nitrogen Management

Groundwater is an important source of drinking water in California. Federal and state limits for nitrate concentration in drinking water (10 ppm NO₃-N, or 45 ppm NO₃) have been exceeded in a large percentage of wells throughout much of California's agricultural regions. Much of the nitrate found in groundwater systems of the Central Valley, Salinas Valley, and other agricultural areas of the state have been attributed to leaching from the crop root zone. For more detailed information, refer to the California Water Boards Nitrate Project website, https://www.waterboards.ca.gov/water_issues/programs/nitrate_project/.

Even relatively low concentrations of nitrate of 1 to 2 ppm N in surface waterways can impact aquatic ecosystems. Nitrate spurs algae growth that increases biological oxygen demand (BOD), reducing the amount of dissolved oxygen in the water and adversely affecting fish and other aquatic organisms. Improved irrigation management can reduce the volume of surface runoff or drainage that may reach public waterways and decrease the likelihood of environmental impacts.

Expectation of Irrigation Efficiency

Irrigation efficiency is the ratio of applied water consumed by the crop or put to other beneficial uses divided by the total amount of

water applied. It is usually expressed as a percentage. An irrigation efficiency at or near 100 percent indicates that all or nearly all irrigation water that is applied for crop production is put to beneficial use (e.g., crop consumption, salinity management, frost protection). It implies that little or none of the irrigation water escaped as runoff or deep percolation. A very high irrigation efficiency at or near 100 percent efficiency can also indicate deficit irrigation, which may reduce yield potential, produce quality, and farm revenue. Achieving reasonably a high irrigation efficiency while limiting excessive crop water stress sustains high farm productivity and protects surface and groundwater quality from nitrate contamination.

Irrigation efficiency can also be viewed from different scales and time steps. The scale may range from large watersheds to individual farm fields or even individual irrigation blocks within a field. Time steps may range from yearly perspectives to weekly or daily intervals. For example, annual time steps might be used to evaluate the efficiency of water used by many farms within a water district. To inform irrigation and N management at the farm level, irrigation efficiency must be evaluated at field scale for a single irrigation event or the sum of at most a few events. When irrigation efficiency is evaluated for individual irrigation events, it represents the water application efficiency for each event. Evaluating application or irrigation efficiency involves a four-step process.

- 1. Determine the soil moisture depletion** in the crop root zone to know how much water can be applied without resulting in excess that can percolate deeper. This can be determined directly by evaluating the soil moisture with sensors or good visual skills or by estimating crop ET for a specific crop and stage of growth.
- 2. Measure the amount of irrigation water applied.** This is best accomplished by measuring the volume of water applied with a flow meter during the irrigation. Meters installed in agricultural irrigation systems usually measure the cumulative volume of water applied during an irrigation in acre-feet. The volume of water applied during an irrigation event can be divided by the acres of land on which the water was applied to give an average depth of applied water.

3. **Compare the soil moisture depletion to the depth of water applied.** Any water applied in excess of the soil moisture depletion either percolates below the root zone or runs off the field as tailwater.
4. **Estimate the application or irrigation efficiency by dividing the soil moisture depletion by the depth of applied water for the irrigation event.**

It is widely acknowledged that attaining 100 percent application efficiency and irrigation efficiency is unrealistic. This is because no irrigation system can apply water perfectly uniformly across a parcel of

land and because soil type and plant canopy size and demand varies within a field. Historically, an irrigation efficiency of 70 percent has been deemed reasonable, and lower efficiencies deemed unacceptable. Depending on the irrigation method and management practices, an 85 to 90 percent irrigation efficiency may be possible. Crops that can be effectively managed using deficit irrigation strategies or acquire a larger proportion of their water needs from rainfall or the water table may achieve higher irrigation efficiencies.

Opportunities to Improve Irrigation Efficiency

While irrigation management is a fundamental agronomic practice, many other skills are necessary to produce a successful crop. A farmer may grow many types of annual and perennial crops and must consider differences among growing seasons, microclimates, and irrigation system constraints. All fields contain varying soil types with variable infiltration, permeability, and water-holding characteristics, and managers must also be adept with land preparation, plant nutrition, pest control, and harvest operations.

When confronted with a busy and diverse farm setting, the first question is where to begin to improve irrigation efficiency. The first step might be to identify the fields where efficiency is low and where efforts to improve it are likely to realize more benefits, in terms of improved crop production, revenue, and reduced irrigation and N inputs.

The soil textural triangle in figure 1 illustrates that the greatest chance and magnitude of leaching N occurs in sand, loamy sand, and sandy loam soils, especially when combined with gravity irrigation systems such as flood or furrow where the soil controls the water infiltration rate. Clay and silt soils are less prone to leaching N. While soil texture is an important feature that influences leaching, Figure 2 illustrates that other management practices involving cover crops, soil and water amendments, and tillage can also influence deep percolation and N leaching.

Tillage and Irrigations Methods Influence Leaching

Nitrogen leaching is more likely to occur with irrigations that follow deep tillage like ripping, chiseling, plowing, or slip plowing. Deep tillage loosens the soil and increases its porosity. Deep percolation and

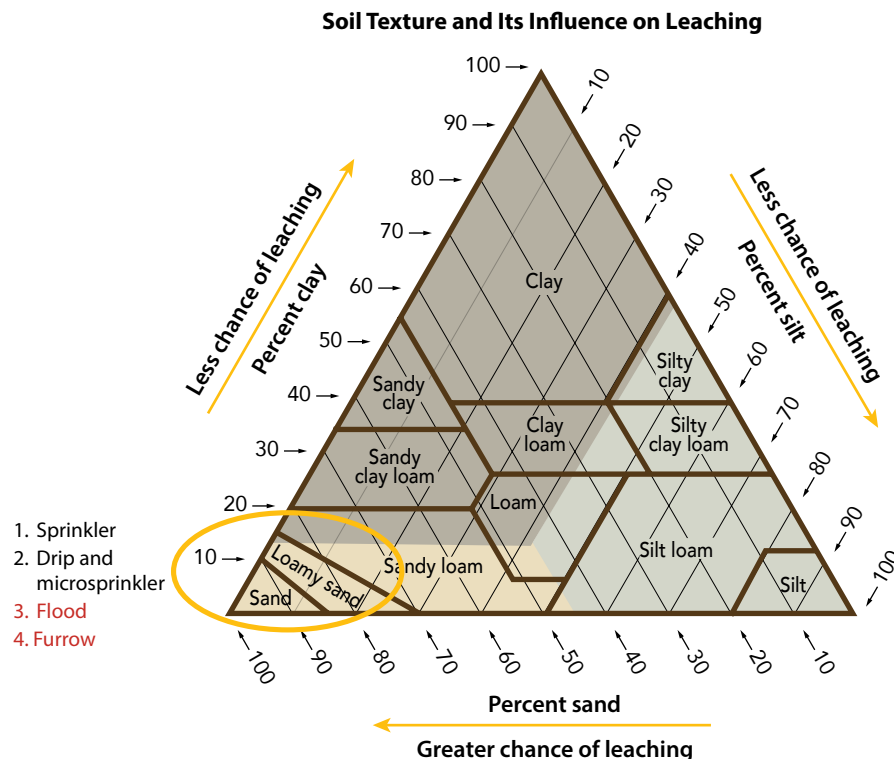


Figure 1. Association between soil texture and risk of leaching nitrogen. Coarse-textured soils in combination with gravity irrigation systems like flood and furrow are more prone to leaching. Source: Dan Munk.

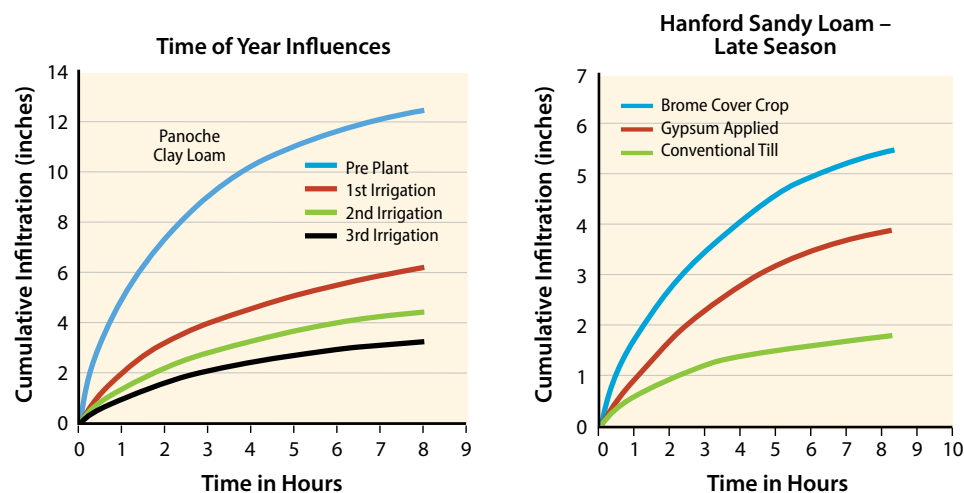


Figure 2. Infiltration rates of water are influenced by management practices. The graph on left shows that higher total water infiltration occurs during preplant irrigation. Cumulative infiltration is about 5 times greater for a preplant irrigation where deep tillage (ripping) commonly occurs before water is applied than for the third crop irrigation where there has been no recent tillage. The graph on the right shows how cover crops and soil or water amendments can also increase the amount of water infiltrated. Source: Dan Munk.

leaching of N is less likely to occur after tilled land has been rained on or irrigated and had the opportunity to settle and reduce the soil porosity. This is particularly the case if soil crusts, or seals, develop at the surface and restrict infiltration.

Generally, it is acknowledged that higher water application and irrigation efficiencies may be achieved with pressurized systems such as drip, microsprinklers, and sprinklers than with furrow or flood irrigation, which rely on gravity to distribute water across a field. Pressurized systems use either drip emitters, microsprinklers, or sprinklers to apply the same amount of water in all areas of a field. They apply water to the crop at low rates that match the infiltration and permeability rates expected for the soil. Pressurized systems require sound design and a long-term commitment to maintain the irrigation system components to achieve and sustain their potential.

With flood irrigation, water must advance down a furrow or across a field. Some furrow and flood irrigation systems can achieve

high application efficiencies. This is most likely to occur on land with relatively uniform soil throughout the field. Higher furrow and flood application efficiencies are likely to occur on clay, clay loam, silt, and some sandy loam soils with lower infiltration and permeability.

When trying to identify where to focus limited time and resources to improve water application and irrigation efficiencies and N management, look for situations where crops are most sensitive to water stress and soils are highly variable and contain sandier soils with higher permeability. Look for irrigation systems that are not applying water uniformly or in controlled amounts. Examining fertilizer, energy, or water bills for inflated costs and crop production history for low yields and unsatisfactory crop quality will guide you where to focus your efforts.

Key Management Decisions and Actions

While the performance of pressurized irrigation systems such as drip, microsprinkler, and sprinkler is mostly governed by the design of components and operation, the performance of gravity systems such as flood and furrow is influenced more by physical soil properties and land preparation. The level of irrigation efficiency achieved with both types of system ultimately depends on reoccurring management decisions and how they are executed. These decisions and actions affect the uniformity of applied water, irrigation frequency, and irrigation duration.

Irrigation Uniformity

Irrigation uniformity is a measure of how evenly water is applied to a field. It is commonly referred to as distribution uniformity (DU) and expressed as a percentage. Equation 1 shows how to approximate DU. When an irrigation system applies water at a high DU, it is possible to achieve high efficiencies in water application and seasonal irrigation. Similarly, when irrigation is uniform, crop production and quality is often higher, which may boost revenue potential. Low DU and the resulting low water application efficiency cannot be improved by managing irrigation frequency or duration. Attention to irrigation system design and maintenance is crucial.

Eq. 1

$$\text{DU (\%)} = (\text{Average volume, pressure, or opportunity time for lowest 25 percentile of measurements} \div \text{Average volume, pressure, or opportunity time of all measurements}) \times 100$$

No irrigation system can apply water perfectly uniformly across a field. A DU less than 70 percent is considered poor for pressurized systems. Ideally, the DU of a pressurized system should be maintained at 85 percent or higher. In contrast, a DU of 70 percent for gravity systems such as flood and furrow is reasonable and a DU of 80 percent or higher would be exceptional.

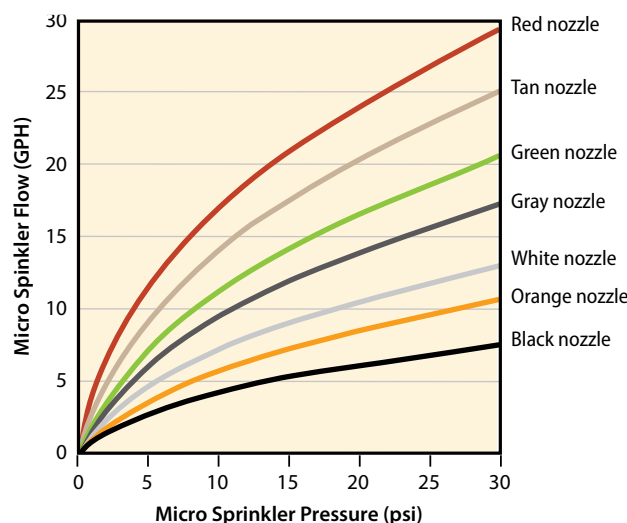


Figure 3. The photo shows a 60 psi liquid-filled pressure gauge connected to a brass pitot tube. This can be used to measure pressures in lateral lines and at nozzles of microsprinklers and solid-set sprinklers. Pressure measurements can be compared with technical information for specific emission devices (an example is on the right) to determine how much the pressure variation may be affecting water discharge rates and irrigation uniformity. A 15 psi or 30 psi pressure gauge would be more appropriate for drip irrigation systems. Source: Allan Fulton.

Measuring Distribution Uniformity in Pressurized Systems

There are several protocols for measuring DU, and some public agencies and private businesses perform irrigation system evaluations upon request. A web search for mobile irrigation labs is one way to identify where these services are available in California. Currently, public entities operate mobile irrigation labs in the vicinity of Kern, San Luis Obispo, Ventura, Napa, and Tehama Counties. However, many growers across the state do not have access to mobile irrigation services at a low cost, which can limit access to detailed irrigation evaluation information. If professional evaluations are not readily available, it is possible for farm staff to evaluate irrigation DU at a preliminary level to help identify potential opportunities to improve irrigation efficiency. It is simpler to measure the DU of pressurized systems than flood or furrow systems.

With pressurized systems, a graduated measuring container and a stopwatch can be used to measure the rate of water discharged from several (at least a total of 15) drip emitters or microsprinklers. Measurements are taken from a minimum of 5 devices in areas near the source of the irrigation water, at a minimum of 5 devices at a mid-way point from the water source, and a minimum of 5 devices farthest away from the source of the water. Alternatively, a pressure gauge and pitot tube could be used at the same points in a field to measure uniformity of system pressures and determine whether they meet the requirement of the emission device (fig. 3). The assumption is that uniform pressures equate to uniform water discharge flows. This is usually a reasonable assumption, but it may not always be accurate if the drip emitters or sprinklers have wear and tear. For further reading on measuring distribution uniformity of drip and microsprinkler irrigation, see Burt 2004 in the references at the end of this publication.

Measuring Distribution Uniformity in Flood and Furrow Systems

Measuring DU in flood and furrow systems is more challenging than in sprinkler systems but it can be done. Figure 4. illustrates two phases of furrow and flood irrigation: the advance (A), or storage, phase and the recession (R), or infiltration, phase. The advance phase is the

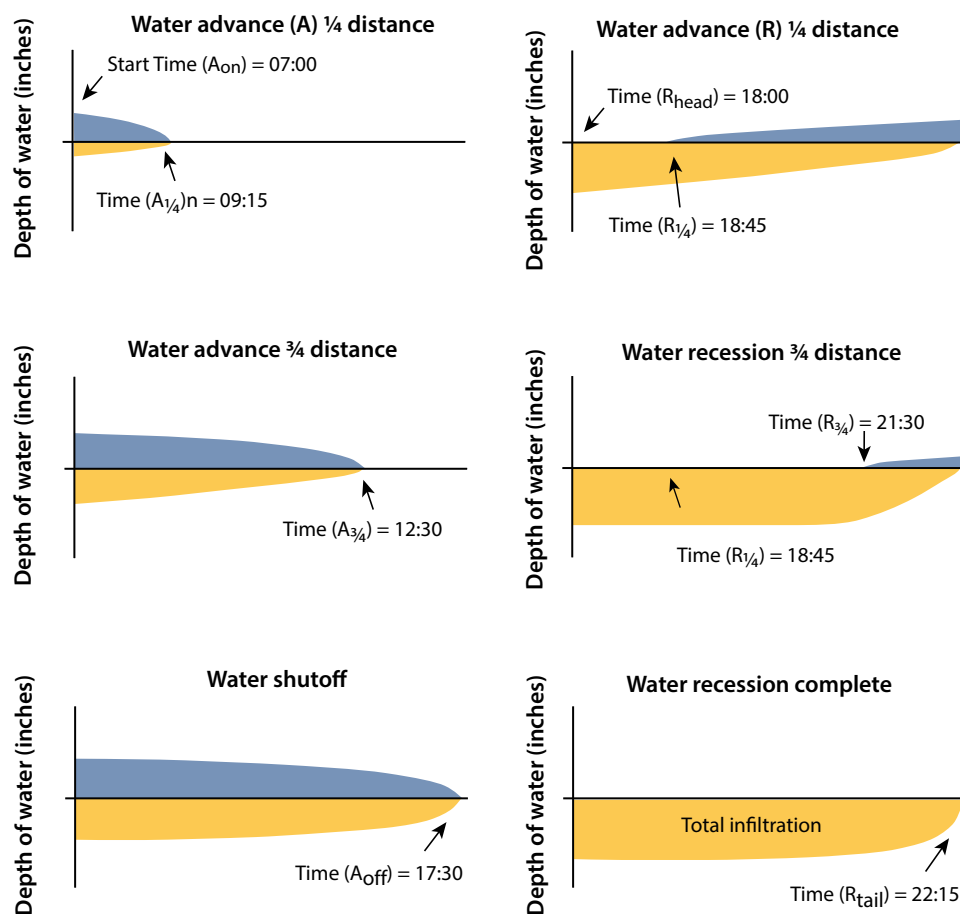


Figure 4. Advance phase (the three graphs on the left) and recession phase (the three graphs on the right) of furrow and flood irrigation and their effect on uniformity of infiltrated water. Advance and recession times are given as an example to approximate DU. Source: Allan Fulton.

portion of the irrigation event in which water flows by gravity down all of the furrows or field surface to the lowest end of the field. When water reaches the end of the field, more water is discharged into the furrows or irrigation basins until enough water is applied to replenish soil moisture depleted by the crop. The water is then turned off, and the recession or infiltration phase into the crop root zone is completed.

Evaluation of water advance and recession in as few as six to twelve furrows or two or three flood irrigation checks should provide a representative field sample. When evaluating furrow irrigation, include furrows both with and without wheel traffic to reflect differences in soil roughness and compaction. This process measures the time that water is in contact with the soil surface, known as the intake opportunity time. To measure opportunity time, record the time when water is turned on, the time when water advances to at least two different points down the furrows or down and across the irrigation checks, and the time when the water is shut off. Suggested measurement points include the start, one-quarter and three-fourths of the distance down the furrows or irrigation checks, and the end of the field (fig. 5). After the flow into the furrows or checks is shut off, record the time when water receded and infiltrated at these points. The opportunity time for infiltration is the time between when the water first advanced to a point and when stored water first receded and infiltrated. Furrow and flood irrigation systems with more consistent intake opportunity times down the furrows and throughout an irrigation check will apply irrigation water more uniformly.

Water Advance Ratio

If evaluating the DU of a furrow or flood irrigation system is impractical for farm staff, a simpler alternative is to determine the water advance ratio. This requires observing how much of the total irrigation time (from the time water is turned on to shut off) is needed for water to reach three-fourths of the distance down the furrows or irrigation checks. To achieve high irrigation DU, this time should not exceed 50 percent of the total irrigation time. Rapid advance times may amplify the need for a tailwater recirculation system or cutting back the inflow rate during the storage phase of the irrigation. A cut-back in the inflow rate may require a variable frequency drive on an electric irrigation pumping plant to make this possible.

Uniform Water Applications with Pressurized Systems

The importance of applying water uniformly with pressurized systems is shown in figure 6. The photo on the left shows a field in which the applied water averaged 1.5 inches across the entire field. Because of how DU is measured and defined (see equation 1, p. 5), and because

Information needed:

Advance times:

Water turn-on time:
Time (Aon) = 07:00

Water advance time to ¼ distance:
Time (A1/4) = 09:15

Water advance time to ¾ distance:
Time (A3/4) = 12:30

Water advance to end of field:
Time (Adone) = 17:30

Recession times:

Water recession at head of field (Rhead):
Time = 18:00

Water recession time at ¼ distance:
Time (R1/4) = 18:45

Water recession time at ¾ distance:
Time (R3/4) = 21:30

Water recession time at end of field:
Time (Rend): 22:15

Calculating “opportunity time” for water infiltration:

Opportunity time at head of field = 18:00 – 07:00 = 13 hours or 780 minutes

Opportunity time at ¼ furrow or check distance = 18:45 – 09:15 = 9.5 hours or 570 minutes

Opportunity time at ¾ furrow or check distance = 21:30 – 12:30 = 9.0 hours or 540 minutes

Opportunity time at end of field = 22:15 – 17:30 = 4.7 hours or 279 minutes

Average opportunity time across field = $((780 + 570 + 540 + 279 \text{ min})/4) = 542 \text{ minutes}$

Average opportunity time low ¼ of field = $((540 + 279 \text{ min})/2) = 410 \text{ minutes}$

Approximate “distribution uniformity” applying Equation 1 (above):

$$\text{DU (\%)} = \frac{410 \text{ minutes average opportunity time low 1/4 of field}}{542 \text{ minutes average opportunity time for whole field}} \times 100 = 76 \text{ \% DU}$$

Figure 5. Example calculation of distribution uniformity (DU) for a flood or furrow irrigation, based on the hypothetical example given in figure 4.

the DU is 90 percent, portions of the field will receive 1.35 inches while other portions of the field will receive 1.65 inches, a difference of only 0.15 inches above and below the average of 1.5 inches. The illustration on the right of figure 6 shows a field where the average depth of applied water was also 1.5 inches. However, the applied water ranged from a minimum of 1.05 inches in the quarter of the field receiving the least water and a maximum of 2.01 inches in the quarter of the field receiving the most water. This represented nearly

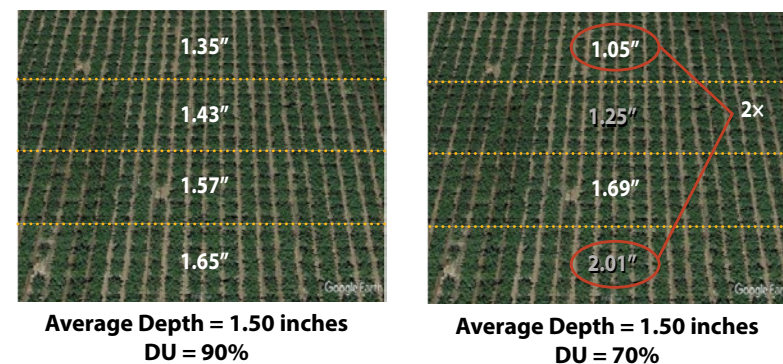


Figure 6. Irrigation distribution uniformity (DU) is important to achieving efficient irrigation and nitrogen management with pressurized irrigation systems. Source: Allan Fulton.

a twofold difference in applied water. If extra water were applied to make sure the low quarter received 1.5 inches of water, the amount of water applied in the high quarter would be even greater and at more risk of deep percolation. Equally important, if N fertilizer were applied through the irrigation system, the rate would not be uniform and at nitrogen would be at more risk of leaching.

Uniformity of applied water with pressurized irrigation systems is tied to the investment in the initial irrigation design and the ongoing commitment to maintain it. Selection of effective filters and pressure regulators and appropriately sized pipelines, tubing, and emission devices are required. Shortcuts in irrigation system designs at the onset to save costs can be difficult and costly or even impossible to correct after a crop is established.

Pressurized systems have several components that will experience wear and tear over time and require checking and repairing on a regular basis. Select durable irrigation designs and components and commit enough labor and time to routinely check system performance, repair broken components, and flush systems regularly. Invest in chemical injection equipment and develop skills using chemigation to manage mineral and biological plugging of emission devices or hire outside firms to perform this service.

Uniform Water Applications with Furrow and Flood Systems

Irrigation uniformity is strongly influenced by soil infiltration and permeability rate and the degree of soil variability in a field. Flow rate, field length, field slope, and surface roughness also affect furrow and flood irrigation uniformity. If long advance times are needed for water to travel from the head of the furrow or basin to the tail, irrigation uniformity will be lower and there will be more risk of water percolating below the root zone. Shorter advance times achieve higher irrigation uniformity across a field but may create more surface water runoff.

Furrow or flood system designs that apply water uniformly include optimal flow rates, field lengths, field slopes, and surface roughness. Shorter field lengths, higher flows into furrows or more flow per square foot of basin, increased slope, and less surface roughness favor more rapid water advance and higher uniformity. It is often beneficial to use higher flow rates or irrigate a smaller area during the earliest irrigations of the season when infiltration rates are highest to help increase uniformity and efficiency. Efficient system elements may also include a tailwater ditch, storage pond, and pumping plant to capture and recirculate surface runoff to other fields. Sustaining an efficient furrow or flood system involves maintaining the designed flow rates, repairing leaks in conveyance pipe and broken irrigation valves, and managing the land grade and surface roughness after major tillage. Flood systems may require rebuilding the berms that guide and contain the water to sustain high efficiency.

Irrigation Frequency and Duration

Decisions about irrigation frequency and duration are often referred to as irrigation scheduling. Low irrigation uniformity cannot be overcome with precise irrigation scheduling, but the benefits of high irrigation uniformity can be compromised if decisions on when and how long to irrigate are off track. The three general approaches to acquire information and make irrigation scheduling decisions include

- water budgeting that is based on monitoring weather, adjusting for phases of crop development, and measuring applied water
- monitoring soil moisture depletion and refill
- direct measurement of crop water stress or plant water status

Water Budgeting

The water budget approach to irrigation scheduling is founded on biometeorological and engineering principles. It is analogous to budgeting money. Soil water storage in the crop root zone equates to a balance in a checking or savings account; crop evapotranspiration (ET_C) or crop water use equates to a debit from the account; and significant rainfall or irrigation equates to a deposit or credit into the account. The management goal is to balance the debits and credits and avoid extreme imbalances. While this is a simple concept, acquiring the needed information and making the calculations can be challenging.

In California, weather instruments are located in reference crops such as well-watered pasture or turfgrass to predict daily reference evapotranspiration (ET_O). The public CIMIS network (<http://www.cimis.water.ca.gov>) conveniently provides free, daily ET_O estimates for many agricultural regions throughout California. The ET_O estimates are used with crop coefficients (K_c) to estimate daily evapotranspiration rates (ET_C) for specific crops. The crop coefficients adjust for various plant densities, crop development phases from germination or bud break through harvest, and crop termination or dormancy.

Daily ET_C approximates soil moisture depletion instead of measuring it directly with soil moisture sensors. Totaling the daily ET_C since the previous irrigation and comparing it with the water-holding capacity of the soil in the crop root zone will help you decide when and how much to irrigate. An example is provided in figure 7 to illustrate the water budget approach.

Finding representative crop coefficients for the diversity of commodities grown in California can be challenging. Appendixes A and B provide crop coefficients for annual and perennial crops, respectively (Hanson et al. 1999). The UC Davis Biometeorology Group offers a Basic Irrigation Scheduling (BIS) program and K_c curves for various California crops (http://biomet.ucdavis.edu/irrigation_scheduling/bis/BIS.htm). The United Nations Food and Agricultural Organization (FAO) Paper 56 (Allen et al. 1998), specifically chapters 6 and 7, offer crop coefficients for many crops grown in California. Several online sources offer support information and tools to help calculate ET_C and perform water budgets. Examples include

- Almond Board of California irrigation management continuum and irrigation calculator, <http://www.almonds.com/irrigation>
- CSU Fresno Waterright, <http://www.wateright.org/>
- UC ANR CropManage decision support tool for vegetable, forage, and tree crops, <https://v3.cropmanage.ucanr.edu/Home/SplashPage?ReturnUrl=%2F>
- UC ANR Sacramento Valley Orchard Source regional real-time weekly ET reports <http://www.sacvalleyorchards.com/et-reports/>
- Washington State University (WSU) Irrigation Scheduler <http://weather.wsu.edu/is/>

New technologies and services are also emerging in the private agriculture sector to support irrigation scheduling and the water budget approach. These technologies and services aim to provide crop evapotranspiration information measured for site-specific growing conditions. Two examples are

- Arable Labs Inc., <https://www.arable.com/>
- Tule Technologies, <https://www.tuletechnologies.com/>

Measuring Applied Water to Budget Effectively

Our ability to manage water improves if we have the ability to measure it. The example of water budgeting in figure 7 uses basic information about the irrigation system design to estimate an hourly water application rate. With pressurized systems, this involves counting the number of drip emitters or sprinklers per acre and knowing the water emission or flow rate for a specific drip emitter or sprinkler head when operated at the optimal pressure. By knowing the hourly water application rate and tracking the irrigation time and frequency, an estimate of the total water applied can be calculated.

As the irrigation pumping plant and system components age or as groundwater levels change, this method of water measurement will need to be repeated. In addition, an updated pump test and irrigation DU will be needed to obtain an accurate estimate of the application rate and uniformity of the irrigation system. Similarly, with furrow and flood irrigation methods, an updated pump test will be needed to determine the flow rate. Irrigation frequency and duration must also

be tracked to estimate the applied water for each irrigation over the course of a season.

Properly installed flow meters are not only a more convenient method to monitor applied water but are often much more accurate than using pump tests and estimates of the irrigation system's

Information needed:

Cumulative ETc since last irrigation or significant rainfall:	1.5 inches for almonds
Average hourly water application rate of sprinkler system:	0.07 inch per hour
Soil water-holding capacity of 4-foot root zone:	6.0 inches

(Soil moisture in the root zone was evaluated and determined to be at field capacity prior to ETc accumulation. Field capacity represents a root zone with soils that have high moisture content but are well drained and not saturated.)

Decision Process:

1. 1.5 inches of ETc is estimated to represent 25 percent depletion of plant-available water in the root zone. This was deemed a desirable and reasonable level of depletion.
2. $1.5 \text{ inch depletion} \div 0.07 \text{ inch per hour water application rate} = 21.5 \text{ hours of irrigation to refill ETc.}$
3. Additional hours of irrigation may be needed to compensate for nonuniformity. As an example, if the distribution uniformity (DU) of a microsprinkler system is 90 percent, an additional 2 hours of irrigation may be appropriate to ensure that all areas of the orchard receive enough water.

Figure 7. Example of water budgeting in almonds for a short time step. Crop evapotranspiration (ETc) is balanced with the depth of water applied. Hours of irrigation duration is calculated based on cumulative ETc since last irrigation and hourly water application rate.

application rate. Flow meters provide an ongoing record of when and how much water was applied during the growing season for the entire irrigated acreage. Several manufacturers offer flow meters for use in irrigated agriculture; some examples are shown in figure 8.

Flow rates are measured and expressed as a volume of water per unit of time, determined by measuring two components: water velocity and cross-sectional area of the pipe or conveyance ditch. Common flow rate units are gallons per minute (gpm) and cubic feet per second (cfs); 1 cfs equals 448.6 gpm.

In agriculture, there are two general types of flow meters for measuring flow in closed pipes: point velocity meters and velocity averaging flow meters. In figure 8, the insertion paddle wheel meter is a point velocity meter. The two impeller meters, magnetic meter, and Doppler meter are velocity averaging flow meters.

As the name and description imply, insertion meters consist of a small paddlewheel that is inserted into the pipe and spins in flowing water to detect the flow velocity. It is inserted through a port on the outside of the pipe to a specific depth in the pipe that is expected to represent the average flow velocity of water inside the pipe. An insertion meter is usually among the less-expensive options and is somewhat adaptable to different pipe diameters.

Impeller meters, magnetic meters, and Doppler meters measure the velocity across the entire cross-section of flowing water inside a pipe. Impeller and magnetic meters must match the pipe size, whereas Doppler meters are more adaptable to a range of pipe sizes. The impellers spin in the flowing water to measure velocity, whereas the magnetic meter uses a magnetic field to track the velocity of water in a pipe. The Doppler meter uses an acoustic sensor; in figure 8, it is temporarily mounted externally on the pipe and uses sound waves to track the water velocity. Other styles of acoustic meters are installed directly in the pipeline, much like the magnetic meter. Impeller meters are usually less costly than magnetic or Doppler meters but may require more maintenance due to more moving parts. The magnetic and Doppler meters work well in water supplies with debris and sediments, as there are no internal parts to tangle or wear; they tend to be more expensive than impeller meters.



Figure 8. Examples of flow meters that can be used in irrigated agriculture. From left to right, an insertion paddle wheel meter, two impeller meters, a magnetic meter, and a Doppler meter.

Accurate measurement with all flow meters depends on proper installation. Position a meter to assure an adequate length of straight pipe both before and after the meter to prevent turbulent or jetting water velocities inside the pipe. A generous rule of thumb is to position the meter so that there are ten pipe diameters of straight pipe before the flow meter and five pipe diameters after the meter. Not all meters have the same requirements. For example, some magnetic meters are accurate with as little as two pipe diameters of straight pipe before and after the meter, while some Doppler meters may need more straight pipe after the meter than before it. Techniques such as inserting straightening vanes before the meter can help reduce requirements for straight pipe.

Position a meter where the pipe is full of flowing water to obtain accurate measurements. Install a flow meter at a low spot on the pipeline to assure a full pipeline of flowing water. Flow meters are available that can accurately measure flow in a partially full pipe but are not typically used in agriculture because they are more expensive.

The same principles of measuring water velocity and cross-sectional area of flow apply when measuring flow rates and total volumes in open ditches. Weirs, flumes, and other measurement structures may be used. When these structures are used, pressure transducers and dataloggers may be needed to continuously monitor

flow to calculate the total volume applied. The free UC ANR online publication *Low Cost Methods of Measuring Diverted Water* (Forero and Fulton 2013) is one source of information on installing weirs and provides other more comprehensive references.

As alternatives to weirs and flumes, acoustic methods such as Doppler and ultrasound can also be used in an open ditch. Water in an open ditch can also be channeled through a segment of pipe with a flow meter to measure applied water.

Information needed:

Flow meter reading at start of irrigation:	21,634,400 gallons
Flow meter reading at end of irrigation:	24,925,800 gallons
Irrigated acreage:	80 acres
Crop ET since start of crop emergence or last irrigation:	1.3 inches

Useful Conversions

1.0 ac-ft = 325,850 gal

1.0 ac-ft = 12 ac-in

1.0 ac-in = 27,150 gal

Calculating average depth of applied water

Step 1: Calculate net gallons measured: $= 24,925,800 - 21,634,400 = 3,291,400$ gal

Step 2: Convert net gallons measured to ac-ft $= 3,291,400 \div 325,850 = 10.1$ ac-ft

Step 3: Convert ac-ft measured to ac-in $= 10.1 \text{ ac-ft} \times 12 = 121.2$ in

Step 4: Divide ac-in measured by irrigated acreage $= 121.2 \div 80 = \mathbf{1.5 \text{ inches average depth applied}}$

Estimate water application efficiency

One Step: $1.3 \text{ in ET} \div 1.5 \text{ in average depth of applied water} \times 100 = 86.7\%$

Applying Flow Meter Data and Calculating Water Application Depth

While knowing flow rate is important, it is even more important to have a meter that measures the total volume of water that passes through it. This is accomplished by tracking the time that water is flowing through the meter and multiplying it by the instantaneous flow rate. The most common and useful measurement unit of water volume in irrigated agriculture is acre-feet (ac-ft). When water is measured for a single irrigation event in acre-feet, it can be divided by the irrigated acreage to determine the average depth of water applied to the crop for that irrigation. Once calculated, the average depth of applied water can be compared with crop ET as part of a water budget and used to compute water application efficiency. Figure 9 illustrates how to apply flow meter data to calculate the average depth of applied water and water application efficiency.

Pros and Cons of Water Budgeting

If applying science-based techniques of water management is new, water budgeting may be a good place to begin. It considers real-time weather conditions and is usually among the least expensive approaches to irrigation scheduling. The primary cost is installation of a flow meter. Using a water budget will strengthen your understanding of how crop water needs change over a season and how to manage a specific irrigation system to supply them. Water budgeting also takes a field-scale view of crop water needs and water management.

Limitations of water budgeting may be related to how well the crop coefficients and ET_C estimates represent site-specific conditions. Also, in production areas of California with higher rainfall, the irrigation requirement may be less than ET, since crops can acquire a portion of their water needs from other sources of moisture. This proportion depends on depth of soil profile, amount of winter and in-season rainfall, and presence of a shallow water table. The challenge becomes knowing how much less the irrigation requirement would be. Often, after some experience with water budgeting is gained, soil moisture or plant water stress indicators are added as feedback to modify irrigation decisions.

Figure 9. Example of using flow meter data to calculate the average depth of applied water and water application efficiency.

Table 1. Overview of the general types of soil moisture sensors available for irrigation management

Key features	Auger “feel”	Tensiometers	Dielectric sensors	Electrical resistance	Neutron radiation
Basic operation	handle and ribbon soil	measures the tension water adheres to soil	measures dielectric constant of soil	measures electrical resistance	measures neutron slowed by soil moisture
Calibration needs	experience	minimal	yes, soil dependent	yes, soil dependent	yes, soil dependent
Monitoring frequency	before and after irrigation	manual or automatic	manual or automatic	manual or automatic	manual
Zone of measurement	diameter of auger and depth sampled	soil 1 to 2 in. from sensor	about 1 in. from sensor	about 1 in. from sensor	about 10 in. diameter
Maintenance	none	at least monthly: refill with water and check of vacuum gauges	annual	annual	weekly battery charging
Replacement	when auger wears down, several years	several years	variable	usually 3 to 7 years	annual battery packs radiation safety
Effects of salinity, alkalinity	none	none	yes, depends on specific sensor	yes	no
Most suitable Soil Type	all	all	non-cracking soils, sand to sandy clay loam	sandy loam to clay	all
Common companies	AMS samplers, JMC samplers	Irrrometer, Hortaui	Decagon, Sentek, Aquacheck	Watermark	InstroTek, various contract services

Monitoring Soil Moisture Depletion and Refill

Numerous methods and types of soil moisture sensors are available to monitor soil moisture conditions in crops and help gauge when to irrigate and how much water to apply. Ideally, they should be used in conjunction with a water budget, but they can be employed independently. General categories of soil moisture sensors and features are summarized in table 1, and two common sensors are shown in figure 10. Soil moisture sensors can help guide and affirm irrigation scheduling decisions when they are installed properly in the active root zone where water is applied and taken up by the crop.

Figure 11 provides a sample set of soil moisture tension levels taken in a developing, second-leaf walnut orchard grown on Los Robles clay loam during the 2017 season. The trends show that the soils were saturated in April following the wet winter of 2016–17. The soils at all three depths drained to field capacity in May. Beginning in June and continuing through August into early September, cycles of soil moisture depletion and refill became apparent at depths of 18 and 36 inches, with very little depletion evident at 54 inches. The recovery of soil moisture tension levels to near zero after each irrigation at all three sensor depths indicate that sufficient water was applied and infiltrated after each irrigation. General relationships between soil moisture tension and the percent depletion of plant-available water for a clay loam soil suggest that this orchard was not subjected to more than about 30 percent depletion from April through August.

Beginning in early September, irrigation was purposely reduced to stop new shoot growth in these developing trees and encourage the green plant tissue to mature and harden into woody tissue. This was done to reduce the risk of frost damage or cold injury during the fall and winter. The soil moisture tension increased at all three sensors to relatively high levels of up to 200 centibars in September and October. Crop water stress was also monitored with a pressure chamber in the orchard (data not shown). While the soil moisture sensor information alone may have triggered some concern that the trees were too dry in the fall, the crop water stress levels indicated that only mild to moderate crop stress was occurring to slow new tree growth and encourage maturing of past growth.



Figure 10. Two types of soil moisture sensors. Left and middle: Watermark resistance sensors with a datalogger; right: one type of dielectric soil moisture sensor. Source: Watermark photos: Allan Fulton; Dielectric sensor photo: anonymous.

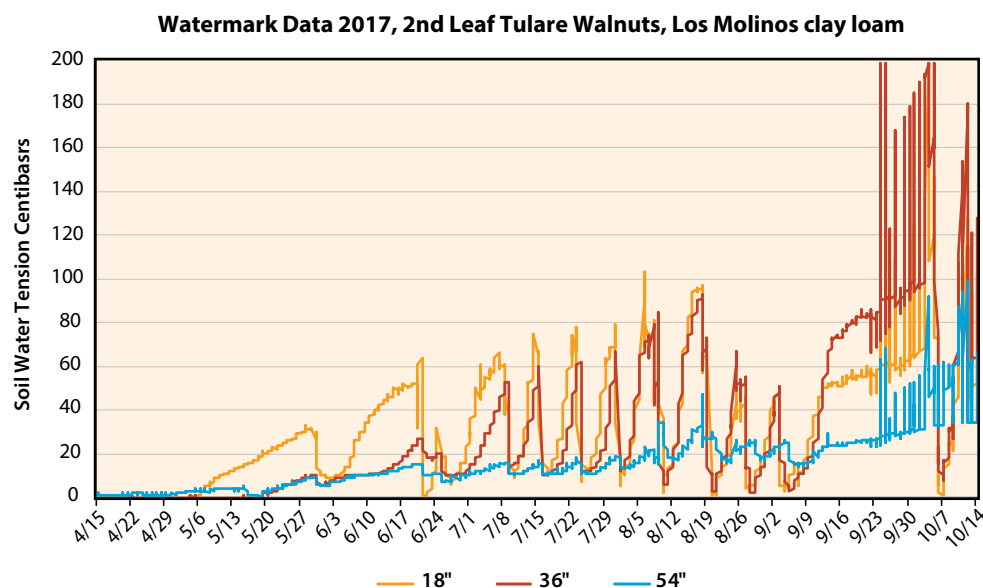


Figure 11. Example of daily soil moisture tension levels measured at three depths in the crop root zone with electrical resistance soil moisture sensors in 2017. Source: Allan Fulton.

Pros and Cons of Soil Moisture Monitoring

When soil moisture sensors are calibrated and properly installed where irrigation water is applied and in the active root zone where water is taken up, soil moisture monitoring can assist with making irrigation scheduling decisions and affirm proper execution. Many types of soil moisture sensors can be automated to deliver current high-frequency measurements to managers on smartphones and other portable computer devices. Soil moisture sensors are also particularly effective at evaluating the duration of an irrigation because they detect the depth of water penetration into the root zone.

Challenges with using soil moisture sensors are being confident that they are placed in locations where water infiltrates and redistributes in the soil and that sensors are installed at depths representing the crop root zone. This is affected by soil variability, irrigation method, type of crop, and proportion of ET_c that may be supplied by rainfall and stored soil moisture as well as by irrigation. Soil sensors measure water content in a small volume of soil, so despite the best efforts, it can be difficult to achieve field-wide representation. Discerning management thresholds for soils of different textures and water-holding capacities and ensuring that the soil sensors are installed and operating correctly are also challenges.

Crop Water Stress

Watching for visual symptoms of crop water stress is a common practice among irrigation managers. Often, an area of a field or orchard that is associated with soils having the lowest water-holding capacity is identified and observed for the earliest signs of canopy darkening and rolling or wilting leaves, which are interpreted as a need for irrigation. This process may provide indications of crop water stress too late for corrective measures to be employed. Vegetative and reproductive phases of crop growth and development that affect yield potential and crop quality may already be negatively impacted before these signs of water stress are visible. These visual symptoms can also be caused by factors other than water stress.

Pressure chambers have been used in California cropping systems for many years to monitor crop water stress and help determine when irrigation is needed. One of the first crops where the tool was

adopted on farms in California was cotton. Since then, pressure chambers have been adapted for irrigation scheduling of perennial crops such as almond, peach, pistachio, prune, walnut, and grape. It is not commonly used in vegetable crops.

What Is Plant Water Stress?

During plant transpiration, water moves from the soil into fine root tips, up through the vascular system, and out into the atmosphere (fig. 12). Water flows through the tree from high potential in the soil (greater than -0.1 bar) to low potential in the atmosphere (less than -40 bars). Low potential is created at the leaf surface through

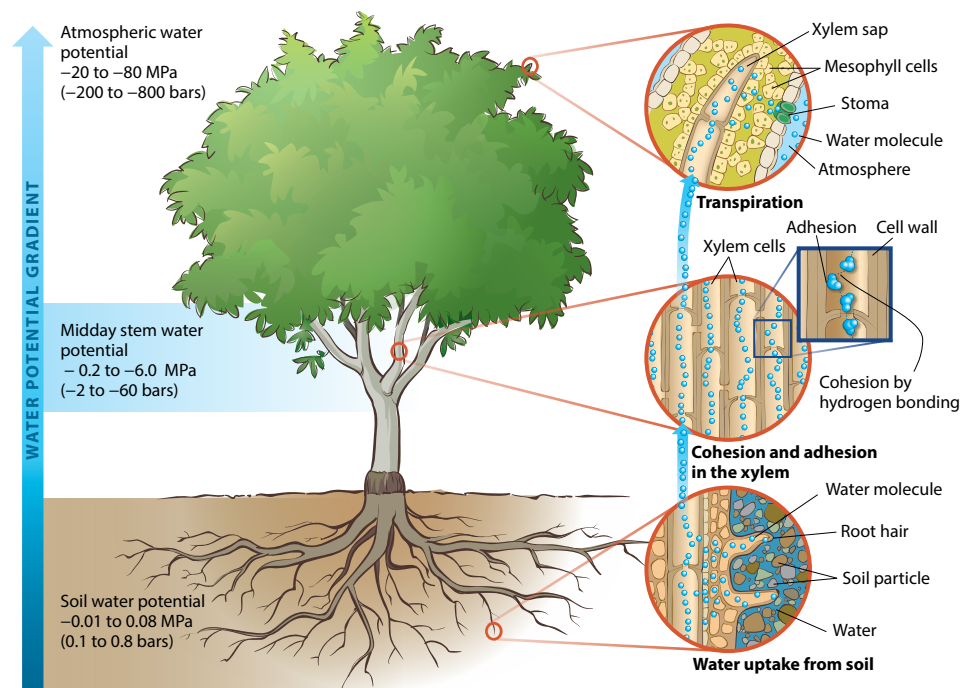


Figure 12. Illustration of how water moves from the soil through an irrigated tree and into the atmosphere, from both a whole-tree and cellular perspective. Stem water potential measures the water potential gradient that drives this movement of water through the tree. Source: Adapted from Pearson 2008. Upper Saddle River, NJ: Pearson Education Inc.

small openings called stomata that open and close to regulate photosynthesis, gas exchange, and plant water loss. Simultaneously, water held in the soil enters root tissue and begins its journey to the leaves. This creates a continuous column of water under tension within the water-conducting system of the plant. The amount of tension depends on the balance between available soil moisture and the rate at which water is transpired from leaves. More tension equates to more plant or crop water stress.

Measuring Crop Water Stress

A pressure chamber measures plant water tension by applying pressure to a severed leaf enclosed in an airtight chamber (fig. 13). The pressure required to force water out of the stem of the leaf is measured by a pressure gauge and equals the water potential. As soil moisture is depleted, more tension develops in the plant, requiring more pressure to force water out of the cut surface of the leaf stem.

Crop water stress is best measured in the midafternoon (mid-day) when plant water demand is highest and more stable, usually between the hours of noon to 4:00 p.m. Select healthy, young, fully expanded leaves for measurement. In tree crops the sample leaf is generally selected from shaded areas in the lower portion (shoulder height) of the canopy near the tree trunk or a large scaffold.

Sampling techniques differ when measuring water stress in different crops. In cotton and wine grapes, leaf water potential is usually measured: an uncovered leaf is cut from the plant or vine and placed inside the pressure chamber to measure the leaf water tension. In almond, walnut, prune, and other tree crops, the most commonly used technique measures stem water potential (SWP): the sample leaf is covered with a foil-laminate bag for at least 10 minutes before it is excised from the tree. The leaf remains in the bag while the measurement is taken with a pressure chamber (fig. 13). As an alternative to stem water potential, shaded leaf water potential is sometimes measured: a small piece of damp cheesecloth is wrapped around the sample leaf, and the leaf is excised immediately from the plant. The wrapped leaf is placed in the pressure chamber to measure the water tension.

Water potential is a direct measure of water tension (negative pressure) within the plant and is given in metric units of pressure,

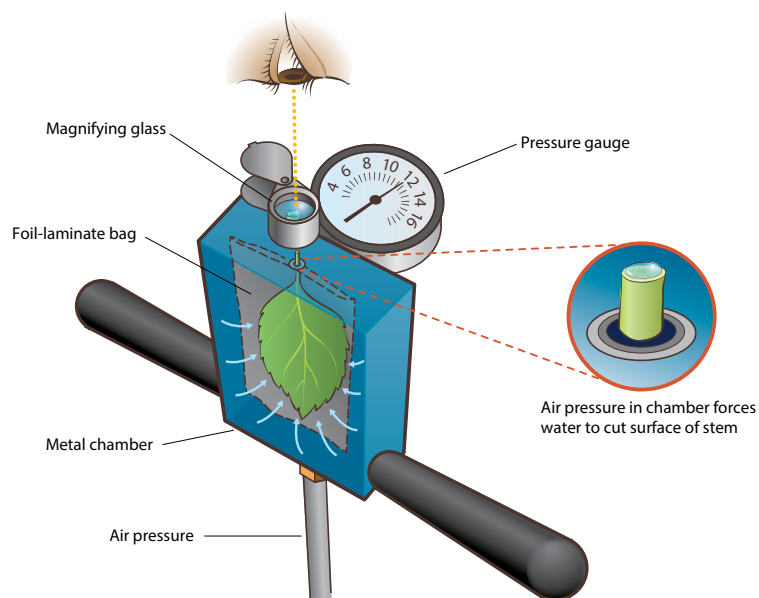


Figure 13. Schematic showing how water potential is measured in a severed leaf and stem (petiole) using a hand-held pump-up pressure chamber. Source: Adapted from Plant Moisture Stress (PMS) Instrument Company.

such as bars (1 bar is about 1 atmosphere of pressure, or 14.5 psi). Technically, SWP should always be shown as a negative value (e.g., -10 bars), but in conversation and because the gauge does not indicate negative values, the negative before the value is often omitted (fig. 14). A larger number on the gauge indicates more plant water stress.

If water potential is measured routinely and especially before and after irrigation, it can quantify patterns of crop water stress and provide valuable insights into when to begin the irrigation season and how frequently the crop should be irrigated. Interpretive guidelines exist for some, but not all, of the major crops grown in California. Guidelines and support tools can be found for various crops in the references suggested below. An example of interpretive guidelines for walnut is also provided in table 2. For useful references

see Bogart 2013; Fulton et al. 2014; PMS Instrument Company 2018; PressureBomb Express.com n.d.; Sanden n.d.; UC ANR 2018.

Pros and Cons of Monitoring Crop Water Stress

Using a pressure chamber to measure crop water stress or status is uniquely different from water budgeting and soil moisture monitoring. It directly quantifies the level of water stress of the crop. Plant water tension is an instant plant water response that can be associated with other important vegetative and reproductive phases of crop development and production. It integrates the soil, plant, and climate variables that affect production. When employed using research-based measurement techniques and interpretive guidelines, monitoring crop water stress has proven to be a reliable and useful monitoring tool to guide decisions on when to begin the irrigation season and the timing of subsequent irrigations.

A constraint to adoption can be that it is relatively labor intensive and requires collecting field data in the heat of the day. However,



Figure 14. Photo of actual SWP measurement in walnut using a pressure chamber with a digital gauge. Plant water status of this walnut tree was -5.67 bars tension. Photo: Carol Haynes.

Table 2. Example of interpretive guidelines for using the pressure chamber and midday stem water potential in walnuts

SWP range (bars)	General stress level	Baseline consideration for		Water stress symptoms in walnut
		Normal or cool weather	Above normal and hot weather	
Higher than -2	none	likely above baseline	very likely above baseline	Not commonly observed, but if measured, they indicate overly wet soil conditions and risk to long-term tree root health. Yellowing tree canopies, small leaves, and nuts may be visible.
-2 to -4	none	at or slightly below baseline	likely to be above baseline	Fully irrigated. Commonly observed when orchards are irrigated according to estimates of real-time evapotranspiration (ETc). If sustained, long-term root and tree health may be a concern, especially on California Black rootstock.
-4 to -6	minimal	as much as 2 bars below typical baseline	at or slightly above baseline	High rate of shoot growth visible, suggested level from leafout until mid-June, when nut sizing is completed.
-6 to -8	mild	may be 2 to 4 bars below baseline	near or possibly above baseline	Shoot growth in nonbearing and bearing trees has been observed to decline. These levels do not appear to affect kernel development or quality.
-8 to -10	moderate	may be 4 to 6 bars below baseline	may be within 2 bars of baseline	Shoot growth in nonbearing trees may stop, nut sizing may be reduced in bearing trees, and bud development for next season may be negatively affected.
-10 to -12	high	may be 6 to 8 bars below baseline	likely 2 to 4 bars below baseline	Temporary wilting of leaves and shrivel of hulls has been observed. New shoot growth may be sparse or absent, and some defoliation may be evident. If sustained, nut size will likely be reduced, with darker kernel color.
-12 to -14	very high	may be 8 to 10 bars below baseline	likely 6 to 8 bars below baseline	Results in moderate defoliation; should be avoided.
-14 to -18	severe	likely 10 to 14 bars below baseline	may be 8 to 10 bars below baseline	Severe defoliation; trees are likely dying.
Below -18	extreme	substantially below baseline under all weather conditions		Not commonly measured in walnut; trees are probably dead or dying.

Source: <http://www.sacvalleyorchards.com/?s=manual>

benefits to production as well as water and energy use efficiency have tended to lessen this concern over the past few decades. Growers who have adopted it successfully into their farm operations are now supporting research development of advanced methods that can monitor crop water stress at a high frequency (almost continuously). They are optimistic that tools capable of monitoring crop water stress at a high frequency would be even more useful. Although a direct measure of crop water stress can be a reliable method of determining when to irrigate, it does not give much insight into how much water to apply or how long to operate the irrigation system when an irrigation is needed.

Concerted Effort Water Budgeting, Soil Moisture Monitoring, and Crop Stress Monitoring

Water budgeting, soil moisture monitoring, and crop stress monitoring have advantages and disadvantages. Water budgeting can provide field-scale information that helps anticipate how much irrigation water needs to be applied and how much time the irrigation system needs to be operated. Soil moisture sensors provide site-specific information that can also help anticipate when to irrigate and determine the depth of water penetration to confirm that the duration of irrigation is on track. Monitoring crop water stress assesses how the

crop is growing in its complex environment and provides feedback to guide when to begin irrigation and how to adjust irrigation frequency. When these methods are used in combination, you will gain additional insight into understanding the crop water system and can be reassured that decisions made in response to that information will result in a sound irrigation management recommendation that is more reliable than if any one method were used.

Other Irrigation Management Considerations

While attention to irrigation DU and irrigation scheduling is important, other management aspects also must be accounted for. They include nitrate-nitrogen in irrigation water supplies; effectively using the irrigation system to deliver N fertilizers to crops; and managing irrigation to control salinity while minimizing the leaching of nitrate-nitrogen.

Nitrate-Nitrogen in Irrigation Water Supplies

Water supplies can contain significant levels of nitrate-nitrogen and be a source of nitrogen for crops. Some groundwater resources, effluent from confined feeding operations, and municipal water treatment plants have potentially high levels of nitrate-nitrogen. Periodic water sampling and laboratory analysis will help identify water supplies with high nitrate-nitrogen content and enable you to account for these sources in an N management plan.

Conversions

From ppm in Irrigation water to lb/ac- in or lb/ac-ft.

<i>Conversion to lb N/ac-in:</i>	<i>Conversion to lb N/ac-ft</i>
ppm (NO ₃) x 0.052 = lb N/ac-in	ppm (NO ₃) x 0.62 = lb N/ ac-ft
ppm (NO ₃ -N) x 0.23 = lb N/ac-in	ppm (NO ₃ -N) x 2.79 = lb N/ac

Figure 15. Equations to convert between NO₃ and NO₃-N levels in water supplies and to convert to levels of elemental N in an acre-inch or acre-foot of water.

Plants are just as likely to take up N from a pound of N in the irrigation water as from a pound of N provided from a fertilizer if the irrigation water is applied uniformly and if the average depth of applied water is not excessive. If irrigations are applied nonuniformly or in volumes that far exceed soil moisture depletion in the root zone, N in the irrigation water may leach below the crop root zone and not be taken up by plants as effectively as would a fertilizer. Organic and inorganic fertilizers contain various forms of N besides nitrate, including organic N, ammonium N (NH₄), and urea, and require time to undergo transformations to the more mobile nitrate form. As a result, not all fertilizer N is as immediately prone to leaching past the root zone as nitrate is in the irrigation water.

Irrigation water supplies should be sampled to establish baseline levels. Supplies with higher or more variable levels of nitrate-nitrogen must be sampled more often. Nitrate-nitrogen levels may be reported differently among analytical laboratories. Labs that specialize in analyzing water quality for drinking water and environmental purposes tend to analyze and report nitrate (NO₃) levels, whereas labs that specialize in analyzing water quality for agricultural suitability tend to report nitrate-nitrogen (NO₃-N) levels. Agricultural labs report NO₃-N, meaning that measured nitrate levels are converted and expressed as elemental N. This is done because N content in available fertilizers, composts, and manures are also measured and expressed as elemental N. By expressing nitrate content in irrigation water as elemental N, these levels can be more easily compared with levels in other N fertilizer sources and included in N management plans. Figure 15 provides conversions between nitrate (nitrate) and nitrate-nitrogen (NO₃-N) and equations to calculate the quantity of NO₃-N per acre-inch or acre-foot of water applied.

Delivering Nitrogen Fertilizers through the Irrigation System

In an effort to match the timing, rates, and placement of nutrients to crops as they consume them, fertilizers containing N and other nutrients are often injected into the irrigation water supply and delivered to crops through the irrigation system. As discussed in earlier sections of this publication, designing, operating, and maintaining irrigation systems that apply water uniformly is critical for this fertilizer

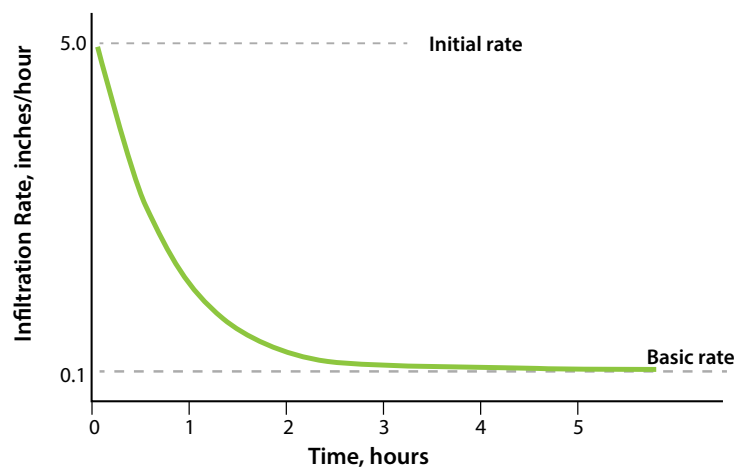


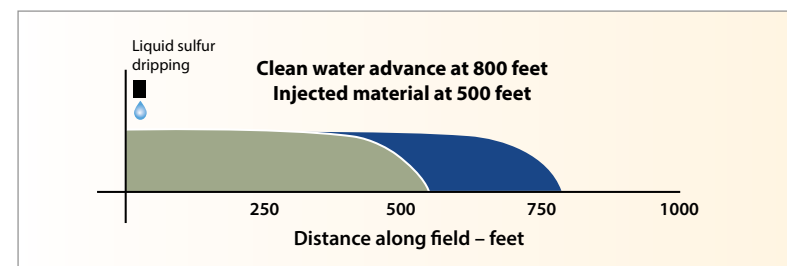
Figure 16. All soils have changing infiltration characteristics. Water infiltrates at initially higher rates when the soil is drier at the start of irrigation. As water is applied and the soil moisture increases the rate of infiltration declines to a basic rate that will remain low until the soil dries out after irrigation.

practice to supply N and other nutrients efficiently and to protect groundwater quality.

Understanding the basic principles of how water infiltrates into soil will help deliver fertilizers efficiently in furrow and flood irrigation systems (figure 16). With furrow and flood irrigation, there is usually an extended period of time (several days, possibly as much as 2 or 3 weeks) between irrigations. Because of this longer interval between irrigations, the soil in the root zone dries out substantially due to crop water use. When irrigation water is applied into a dry furrow or irrigation check, the initial infiltration rate starts off higher and then slows to lower levels (referred to as the basic or steady state) as the soils are irrigated.

As discussed earlier, infiltration characteristics of soils depend on soil texture and structure, which can be influenced by cover cropping and other practices that increase soil organic matter, stability of soil structure and porosity, and water-holding capacity. The extent of tillage operations before irrigation and the use of soil and water amendments can also affect soil infiltration characteristics.

Results from a field study conducted in the San Joaquin Valley (figure 17) show how fertilizers can be applied more uniformly and in smaller, more controlled quantities by delaying the injection of liquid fertilizers until much of the water advance phase of a furrow or flood irrigation event is completed. Liquid sulfur was used in the experiment because it was visible in the water and more easily tracked. In this field example, there was potential to apply extraordinarily high rates of N that exceeded crop needs when fertilizers were injected during the entire irrigation event. When fresh water was allowed to advance from 75 to 85 percent of the field length before injecting fertilizer, the amount of fertilizer was controlled to lower rates that matched better with amount needed by the crop during specific phases of development. Meanwhile, the advance of the untreated freshwater at the far end of the field was much slower because it was traveling over dry, unirrigated soils with much higher initial rates of water infiltration.



Flood Irrigation Field Study:

field length 1200', average irrigation amount = 7.1"

Fertigation added	Nitrogen applied (lb/ac)	Uniformity of application
During entire irrigation	242	+
When freshwater advance at 75% length	86	++
When freshwater advance at 85% length	31	+++

Figure 17. Example of how understanding the basic principles of water infiltration can increase control over the rate and uniformity of fertilizers applied with a furrow or flood irrigation system. Source: Larry Schwankl.

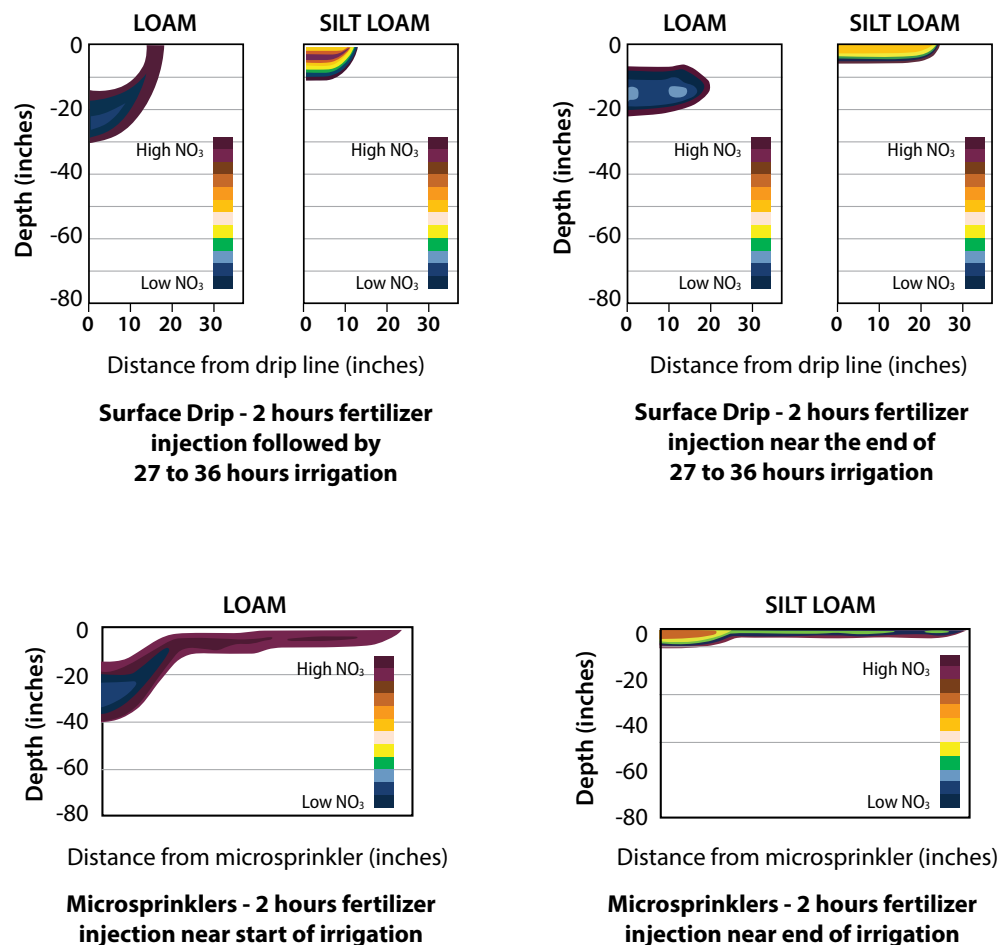


Figure 18. Soil texture can influence the distribution of N fertilizers in crop root zones. In this example, mobile N fertilizers penetrated deeper into the root zone of a lighter-textured loam soil than in a medium silt loam soil. Also, decisions related to when and how long a fertilizer is injected during an irrigation set will affect how N is distributed in the crop root zone. Shorter injection times (2 hours in this example) with the injections made near the end of an irrigation set help keep the fertilizer in the shallow portions of the root zone, improving the chance of crop uptake and lessening the chance of leaching. Consider that the fertilizer injection in this example was followed by additional irrigations without fertilizer injections. Source: Hanson 2006.

Understanding how fertilizers travel through a drip or micro-sprinkler irrigation system and how they are redistributed in the crop root zone after they have been applied also helps assure that fertilizers are applied efficiently through an irrigation system. Since drip and microsprinkler irrigation systems vary in design (injection rates, pipe sizes, pipe lengths, and lateral line sizes and lengths), there is no standard travel time for fertilizers through a system. In one UC study (L. Schwank., pers. comm.) of six different systems, fertilizers and maintenance chemicals required from 30 to 75 minutes to travel from the point of injection to the farthest drip emitters or sprinklers in the system.

Knowing the fertilizer travel time enables you to make sure that all portions of a field receive enough fertilizer to supply crop needs and that all of the fertilizer is purged from the irrigation system before it is shut off. It is best to evaluate the travel time for each irrigation system. This can be done most easily by injecting liquid chlorine and using a simple swimming pool test kit to measure the chlorine presence as it moves through the system. This needs to be done only once and should represent the travel time of the system unless a substantial modification is made to the injection equipment or system design.

Also, consider when to inject the fertilizer relative to the total irrigation time and the total water applied during an irrigation. Choosing to inject a fertilizer at the beginning, middle, or end of the irrigation affects the redistribution of the fertilizer in the crop root zone and can affect the chances of leaching N below the root zone toward the groundwater (figure 18). Soil texture and water-holding capacity also affect the distribution of N and other fertilizers in the root zone.

Managing Irrigation for Salinity Control

As discussed earlier, irrigating to control salinity in the crop root zone is a beneficial use of water. Extra water beyond quantities needed to meet crop water demand is applied to leach salts out of the crop root zone and prevent osmotic effects and specific ion toxicities (figure 19). The challenge is to manage irrigation and effectively leach salts from the root zone without leaching NO_3 from the crop root zone.



Figure 19. In many instances, irrigation is needed to control salt buildup in the soils of the crop root zone to prevent crop injury, as shown in the photos above. These photos show severe crop damage in walnut resulting from accumulation of sodium. Other specific elements, such as boron and chloride, can accumulate as well if they persist in the soil and water. Osmotic effects or too much total salinity in root zone can also damage the crop but these symptoms are not shown. Usually, specific ion toxicity will be expressed before osmotic effects. Photos: Blake Sanden

Some tips to leach salts while minimizing leaching of NO_3 are given below.

- Leaching is not necessary every irrigation or perhaps even every season; it is necessary only when crop tolerances are approached.
- Periodic soil and irrigation water testing helps determine when leaching is needed.
- For leaching to occur, the amount of applied water must exceed crop ET, and the soil moisture content must exceed field capacity.
- Leaching should be conducted as late as possible after the previous fertilization.
- Leaching is most efficient in the winter on fallow land or when crops are dormant and should not coincide with critical periods of N fertilization and uptake.
- Refer to Cahn and Bali 2015 for additional information.

Summary

Regulations on N management continue to increase for irrigated agriculture in California to protect groundwater quality for drinking and to enhance environmental water quality. Irrigation management directly affects N use efficiency, so it must also be considered at the farm level to successfully manage nitrates in agriculture. This complex matter can be overwhelming if not approached strategically. Some suggestions to proactively engage this issue at the farm level include the following.

- Identify fields that are the least efficient in terms of production potential and N, water, and energy inputs. In these situations a win-win can most likely be achieved in terms of sustaining or improving the farm and protecting water quality. They are a starting point to build on.
- Develop skills in evaluating irrigation DU, if only at a precursory level. Then identify irrigation systems with the lowest DU and work to improve them or replace them with better systems.
- Expand your knowledge of chemigation methods and invest in efforts to maintain irrigation systems.
- Improve your expertise in measuring water and in climate, soils, and plant-based techniques for determining when to begin irrigation, how often to irrigate, and how much water to apply.

References

- Allen, R., L. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Paper 56. Rome: Food and Agriculture Organization of the United Nations.
- Bogart, K. 2013. Measuring winegrape water status using a pressure chamber. eXtension website, <http://articles.extension.org/pages/33029/measuring-winegrape-water-status-using-a-pressure-chamber>.
- Burt, C. 2000. Rapid field evaluation of drip and microspray distribution uniformity. Irrigation and Drainage Systems

- 18: 275–297. <https://link.springer.com/article/10.1007/s10795-004-2751-x>.
- California Water Boards Nitrate Project website, https://www.waterboards.ca.gov/water_issues/programs/nitrate_project/.
- Cahn, M., and K. Bali. 2015. Drought tip: Managing salts by leaching. Oakland: University of California Agriculture and Natural Resources Publication 8550. UC ANR catalog website, <https://anrcatalog.ucanr.edu/Details.aspx?itemNo=8550>
- Forero, L., and A. Fulton. 2013. Low-cost methods of measuring diverted water. Oakland: University of California Agriculture and Natural Resources Publication 8490. UC ANR catalog website, <https://anrcatalog.ucanr.edu/Details.aspx?itemNo=8490>.
- Fulton, A., J. Grant, R. Buchner, and J. Connell. 2014. Using the pressure chamber for irrigation management in walnut, almond, and prune. Oakland: University of California Agriculture and Natural Resources Publication 8503. UC ANR catalog website, <https://anrcatalog.ucanr.edu/Details.aspx?itemNo=8503>.
- Hanson, B. 2006. Fertigation with microirrigation. Oakland: University of California Agriculture and Natural Resources Publication 21620.
- Hanson, B., L. Schwankl, and A. Fulton. 1999. Scheduling irrigations: When and how much water to apply. Oakland: University of California Agriculture and Natural Resources Publication 3396.
- PMS Instrument Company. 2018. Interpreting data. PMS Instrument Company website, <https://www.pmsinstrument.com/resources/interpreting-data>.
- PressureBomb Express. N.d. Website, <https://www.pressurebomb-express.com/>.
- Sanden, B. N.d. Bomb your cotton for maximum profit. PMS Instrument Company website, <https://www.pmsinstrument.com/resources/bomb-your-cotton-for-maximum-profit>.
- UC ANR (University of California Agriculture and Natural Resources). 2018. Sacramento Valley Orchard Source website. <http://www.sacvalleyorchards.com/?s=Pressure+Chamber>.

©2019 The Regents of the University of California.

The University of California, Division of Agriculture and Natural Resources (UC ANR) prohibits discrimination against or harassment of any person in any of its programs or activities on the basis of race, color, national origin, religion, sex, gender, gender expression, gender identity, pregnancy (which includes pregnancy, childbirth, and medical conditions related to pregnancy or childbirth), physical or mental disability, medical condition (cancer-related or genetic characteristics), genetic information (including family medical history), ancestry, marital status, age, sexual orientation, citizenship, status as a protected veteran or service in the uniformed services (as defined by the Uniformed Services Employment and Reemployment Rights Act of 1994 [USERRA]), as well as state military and naval service.

UC ANR policy prohibits retaliation against any employee or person in any of its programs or activities for bringing a complaint of discrimination or harassment. UC ANR policy also prohibits retaliation against a person who assists someone with a complaint of discrimination or harassment, or participates in any manner in an investigation or resolution of a complaint of discrimination or harassment. Retaliation includes threats, intimidation, reprisals, and/or adverse actions related to any of its programs or activities.

UC ANR is an Equal Opportunity/Affirmative Action Employer. All qualified applicants will receive consideration for employment and/or participation in any of its programs or activities without regard to race, color, religion, sex, national origin, disability, age or protected veteran status.

University policy is intended to be consistent with the provisions of applicable State and Federal laws.

Inquiries regarding the University's equal employment opportunity policies may be directed to: Affirmative Action Contact and Title IX Officer, University of California, Agriculture and Natural Resources, 2801 Second Street, Davis, CA 95618, (530) 750-1397. Email: titleixdiscrimination@ucanr.edu. Website: http://ucanr.edu/sites/anrstaff/Diversity/Affirmative_Action/.

To simplify information, trade names of products have been used. No endorsement of named or illustrated products is intended, nor is criticism implied of similar products that are not mentioned or illustrated.

This publication was partially funded by the California Department of Food and Agriculture. The contents may not necessarily reflect the official views and policies of the State of California.