# The Pressure Chamber – Does It Have a Place in Your Tool Box?

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Among the most basic observations that can be used to manage irrigation in orchard crops are visual cues of crop water stress. However, these cues can be somewhat subjective and are often expressed after plant stress is higher than desired. Measuring midday stem water potential (SWP) using a pressure chamber is a quantitative method for evaluating plant water status, and relationships have been established between pressure chamber measurements and tree growth and productivity. From these relationships, guidelines have been developed to assist growers in making irrigation scheduling decisions.

This is an abbreviated discussion of pressure chamber operation and interpretation of measurements based upon peer-reviewed UC ANR Publication 8503, *Using the Pressure Chamber for Irrigation Management in Walnut, Almond, and Prune* (2014).

## *Plant Water Status*

During plant transpiration, water moves from the soil into fine root tips, up through the vascular system, and out into the atmosphere (fig.1). Water flows through the tree from high potential in the soil (about –0.1 bar) to low potential in the atmosphere (less than –40 bars). Low potential is created at the leaf surface through 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 vacuum, or continuous column of tension within the water-conducting system of the tree. The amount of tension depends on the balance between available soil moisture and the rate at which water is transpired from leaves.

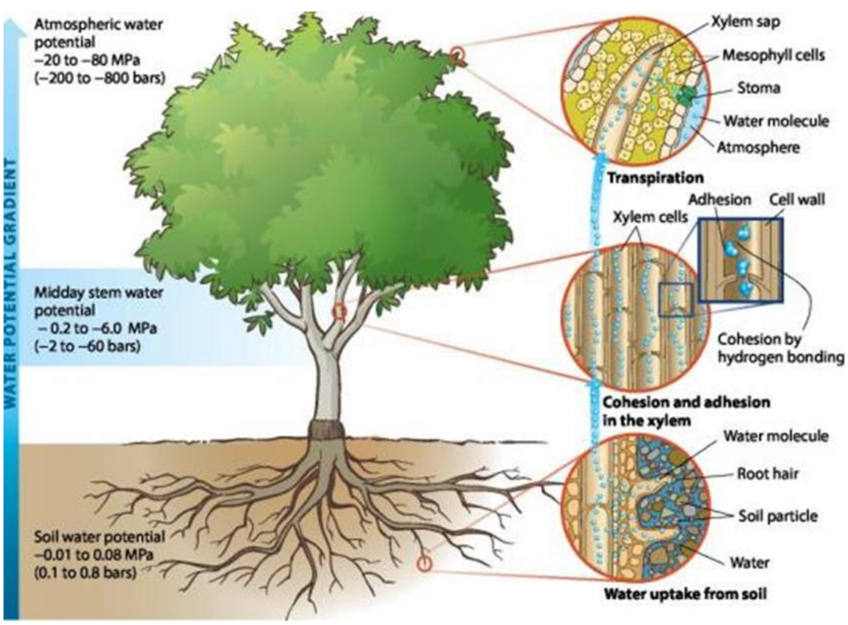


**Figure 1.** Illustration of how water moves from the soil through an irrigated tree and into the atmosphere, from both a whole-tree and cellular perspective. SWP measures the water potential gradient that drives this movement of water through the tree. *Source:* Adapted from Pearson 2008. Upper Saddle River, NJ: Pearson Education Inc.

## *Midday Stem Water Potential (SWP) Concept*

A pressure chamber measures plant water tension by applying pressure to a severed leaf and stem enclosed in an airtight chamber (fig. 2). The sample leaf is covered with a foil-laminate bag for at least ten minutes before it excised from the tree. The leaf remains in the bag while the measurement is taken. The pressure required to force water out of the stem of a severed leaf equals the water potential and is measured by a pressure gauge. 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.

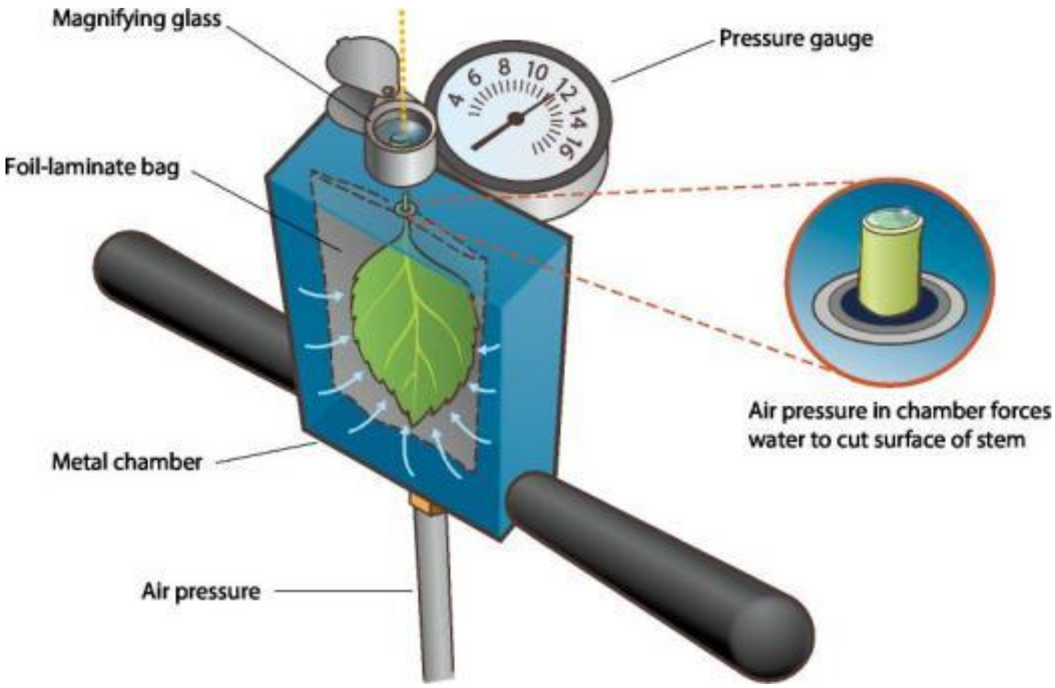


**Figure 2.** Schematic showing how water potential is measured in a severed leaf and stem (petiole) using a hand-held pump-up pressure chamber. *Source:* Adapted from Plant Moisture Stress (PMS) Instrument Company.

Stem water potential is a direct measure of water tension (negative pressure) within the plant and is given in metric units of pressure, 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, we often omit mentioning "negative" before the value. A larger number on the gauge indicates more tree water stress.

## *Pressure Chamber Selection*

A number of companies produce durable, portable, and relatively inexpensive pressure chambers for measuring stem water potential (SWP). All have the same basic components and operate on the same concept. The choice of a pressure chamber depends largely on preferences. Several pressure chamber styles and designs are available, ranging from simple manual pump-ups to consoles with more advanced features (fig. 3). Compressed nitrogen gas is a convenient, relatively inexpensive, and inert (safe) gas to use as a source of pressure. Carbon dioxide gas is also used to supply pressure with some pressure chambers. Compressed air is used with some pressure chamber models. The cost may range from about $1,000 to about $7,000, depending on the style, design, and whether the unit is new or used.

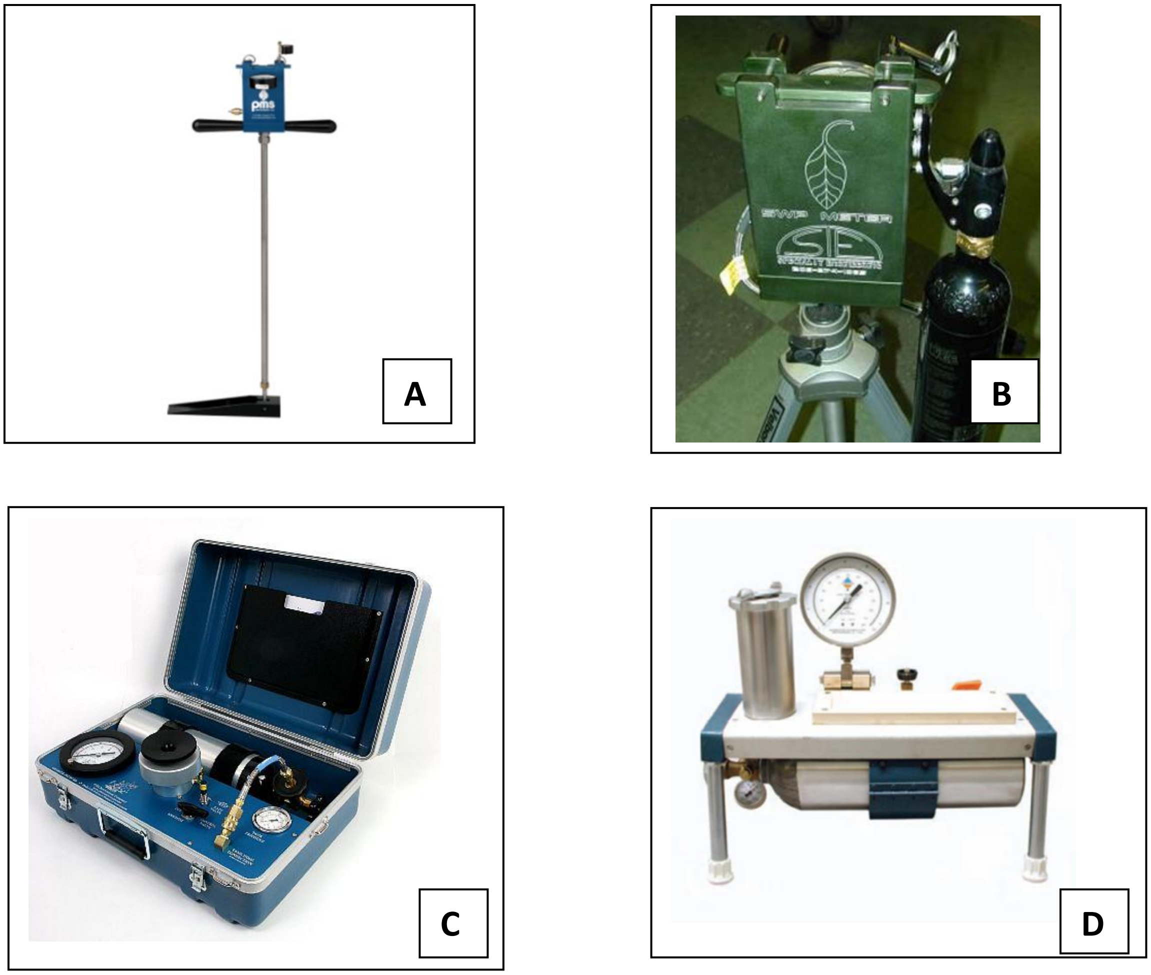


**Figure 3.** Four examples of commercially available pressure chambers. Example A is a pump-up style by PMS Instruments in which a foot pump creates air pressure in the rectangular chamber. Example B, by Specialty Engineering, also has a rectangular chamber, employs a tripod to hold the pressure chamber, and uses compressed carbon dioxide ($CO_2$) gas to supply the pressure. Example C is a suitcase-style pressure chamber. It has a cylindrical chamber that uses nitrogen gas, to pressurize the chamber. Both PMS Instruments and Soilmoisture Equipment Corp. offer this style of pressure chamber. Example D is a console- or bench-style pressure chamber by Soilmoisture Equipment Corp. that also uses nitrogen gas to pressurize the chamber. *Photos:* Courtesy of Plant Moisture Stress (PMS) Instrument Company, Albany, OR (A, C); Specialty Engineering, Waterford, CA (B); and Soilmoisture Equipment Corp., Santa Barbara, CA (D).

## *Costs to Monitor Plant Water Status*

Growers and consultants who already use the pressure chamber and midday stem water potential as one of their management tools indicate the cost to integrate it into their management ranges from about $10 to $20 per acre annually. This is a relatively low cost compared to the cost of water and other production practices. This accounts for the labor to take the measurements, compressed gas (nitrogen or carbon dioxide), time to evaluate the data, and maintenance of the instrument. It does not reflect the cost of purchasing the pressure chamber. Pressure chambers are generally durable if handled and maintained reasonably. It's not uncommon for a pressure chamber to last many years, so the cost of the instrument is generally nominal when amortized over several years and many acres.

## *Making Stem Water Potential Measurements*

### Time of day

Stem water potential (SWP) is best measured midday from 12:00 to 4:00 p.m. The idea is to make measurements when the tree is experiencing relatively constant and maximum water demand. From a practical standpoint, irrigation managers are interested in the highest stress that trees experience, which is also at midday. Thus, the guidelines for interpreting SWP measurements have been made by using midday measurements.

### Time of season

SWP measurements should begin during the spring and continue through the summer and fall. This approach will help indicate when to apply the first irrigation, show how orchard water status responds to irrigation decisions, how irrigation scheduling might be improved and how water status shifts with seasonal weather changes. Postponing SWP measurements until early summer will miss the progressive changes in orchard water status leading up to the summer season (when water demand is highest).

### Time between irrigations

Orchard acreage, time availability, coordination with other tasks, previous experience, and specific interests (troubleshooting) may influence measurement frequency. Not all orchards have to be measured at the same frequency. Measuring SWP just prior to irrigation and one or two days after irrigation provides the most information about the ongoing water status of the orchard. SWP measurements taken just before irrigation will indicate the orchard water status when orchard stress is potentially the highest, and provide insight into whether the interval between irrigations needs to be adjusted. Monitoring SWP one or two days after irrigation will indicate how well the tree water status recovered after irrigation and give insight into whether the duration of irrigation is on track.

Larger changes in SWP may be observed before and after irrigation when irrigation frequency is stretched out more with a flood or sprinkler system that applies more water in a single irrigation. Conversely, smaller, more gradual changes in SWP may be observed with drip and microsprinkler systems that apply water at higher frequency and lower volume. So, it is not necessary or usually feasible to measure SWP before and after every drip or microsprinkler irrigation. Measuring SWP just before a drip or microsprinkler irrigation every 7 to 10 days should provide reasonable trends and insights into the orchard water status.

### How many measurements to make in an orchard

Determining how many trees to monitor must balance having enough trees to reliably represent the orchard and being able to cover the desired total acreage in a timely and efficient manner. Sampling fewer trees and accepting the possibility of less-representative measurements is better than not using SWP at all because it is perceived as too labor intensive. The number of trees to monitor in an orchard also depends on soil variability and irrigation uniformity. Fewer trees are needed if the orchard is growing on one predominant soil type with uniform irrigation. More trees are needed if there is more than one soil type and non-uniform irrigation. A sampling strategy that can be completed in about 30 to 60 minutes per orchard is ideal, especially if several orchards must be monitored on the same afternoon. Understanding of orchard water status will improve as the number of trees monitored is increased. A sample size ranging from 5 to 10 trees per orchard is probably optimal for achieving representative measurements and covering acreage efficiently. One strategy is to start with a greater number of measurement trees and then pare down over time, as the trends and patterns of orchard water status is more understood.

**Selecting trees for measurement**

Trees selected for SWP monitoring should be representative of the orchard. Good measurement trees would be of the same variety and rootstock and similar in age, degree of pruning, and canopy size. Measurement trees should be irrigated in the same manner as the rest of the orchard and should be healthy. The trees selected for SWP measurement should be at least 100 feet inside the orchard and have other healthy trees growing around them. The same trees should be used to measure SWP each time to reduce variation from one day to the next. The sample trees should be marked with flagging, spray paint, GPS waypoints (or a combination thereof), so they are easily located each time SWP measurements are made. Going back to the same trees for each reading, reduces variability and may be more important than the number of trees measured.

When sampling small trees, particularly during the first year, excessive leaf removal may be an issue, especially if the trees are planted later and not growing vigorously. One solution is to identify three or four side-by-side rows of uniformly growing trees in representative areas of an orchard. Each row will have three or four trees identified for SWP measurement. Then, using a rotational schedule, measure SWP in a different row each reading, returning to the first row after trees have had time to grow additional leaves suitable for measurement (usually two or three weeks after the previous measurement). Typically, second-year and older trees should have sufficient canopy, that rotating between rows of sample trees is no longer necessary.

**How many leaves per tree**

To ensure the reading is not compromised by operator error or poor leaf selection, it is important to make two measurements per tree, or a single leaf from two adjacent trees. Compare the readings; if they are more than 0.5 to 1.0 bar apart, another leaf should be measured and the average of the closest leaves recorded. If the difference between the two leaves is great, bag another leaf and return to make the measurement. Then, take the average of the closest measurements. An alternative strategy is to bag three leaves per tree then measure the first two, and if the measured SWP is in good agreement pass on the third measurement.

**Good SWP field measurement technique**

Consistent technique helps improve the accuracy of SWP measurements. On the same almond trees, as much as a 2-bar discrepancy, plus or minus, has been documented with different operators. Such errors can be due to differences in speed and method of handling the sample from the time the leaf is excised until the measurement is completed, or they can be due to differences among operators in recognizing the endpoint. Relying on one operator to check the same orchards over the season, using the same pressure chamber and consistent technique is recommended.

Good SWP measurement technique begins with properly selecting sample leaves and bagging or covering them with a foil-laminate bag (fig. 4). Leaves should be healthy, full grown, and without apparent nutritional deficiencies, yellowing from excessive shading or older age, or physical damage from wind or hail. Lower interior, shaded leaves are selected nearer to larger branches of the tree trunk, where the bagged leaf equilibrates readily with the tree's main water-conducting system. Leaves higher in the canopy or farther out on a limb can give significantly different levels of SWP due to more resistance to water flow through more of the vascular system. Reflective, water-impervious mylar foil bags are commonly used for bagging leaves. Bags are available from some pressure chamber manufacturers. Nylon button fasteners, re-sealable zip fasteners, paper clips, clothes pins and other creative approaches can be used to fasten the foil bags to the leaves.

**Figure 4.** From left to right, healthy full grown leaves are selected in the lower interior canopy of an almond, prune, and walnut tree near larger branches of the trunk and covered with mylar foil bags for at least ten minutes. Walnut has a compound leaf, so the terminal leaflet is selected because it has a longer petiole which assists the measurement. (Photos: A. Fulton)

The importance of bagging or covering the sample leaves on large perennial trees can't be emphasized enough. Ideally, the sample leaves are bagged for at least 10 minutes prior to excising the leaf from the tree. It is acceptable to bag leaves longer than 10 minutes. They may be covered several hours or even a day in advance if it adds convenience.

After the trees with the sample leaves have been bagged for at least 10 minutes, it is time to measure the SWP with a pressure chamber. The leaf must remain enclosed in the bag after it is excised from the tree and placed in the chamber. If the bag is removed at any time, the SWP level will begin to change rapidly (within seconds) as the leaf is exposed to the often hot, windy environment around it. Only using bagged leaves is an important practice in acquiring stable, more-representative measurements that are easily interpreted. Resist the temptation to remove the leaf from the foil bag even if it makes inserting the sample leaf into the chamber more convenient.

Measuring SWP (fig. 5) after the bagged leaf is excised from a tree involves inserting the stem of a bagged leaf upward through the top of the pressure chamber and securing the protruding stem in the pressure chamber cap (A). Then, placing the bagged leaf in the pressure chamber (B). A long stem is shown protruding out of the top of the chamber (C). Some researchers emphasize that the stem should not be protruding out this much for the most accurate measurement of SWP. Other researchers have observed that practitioners have more difficulty seeing the endpoint without the longer stem, which can also introduce error in seeing the endpoint. Apply pressure inside the chamber and determine the endpoint for a SWP measurement. Close to the endpoint, water begins to exude from the surface of the cut stem and will appear to glisten (D). With the addition of a little more pressure, water will cover the entire cross-section of the stem and reach the endpoint.

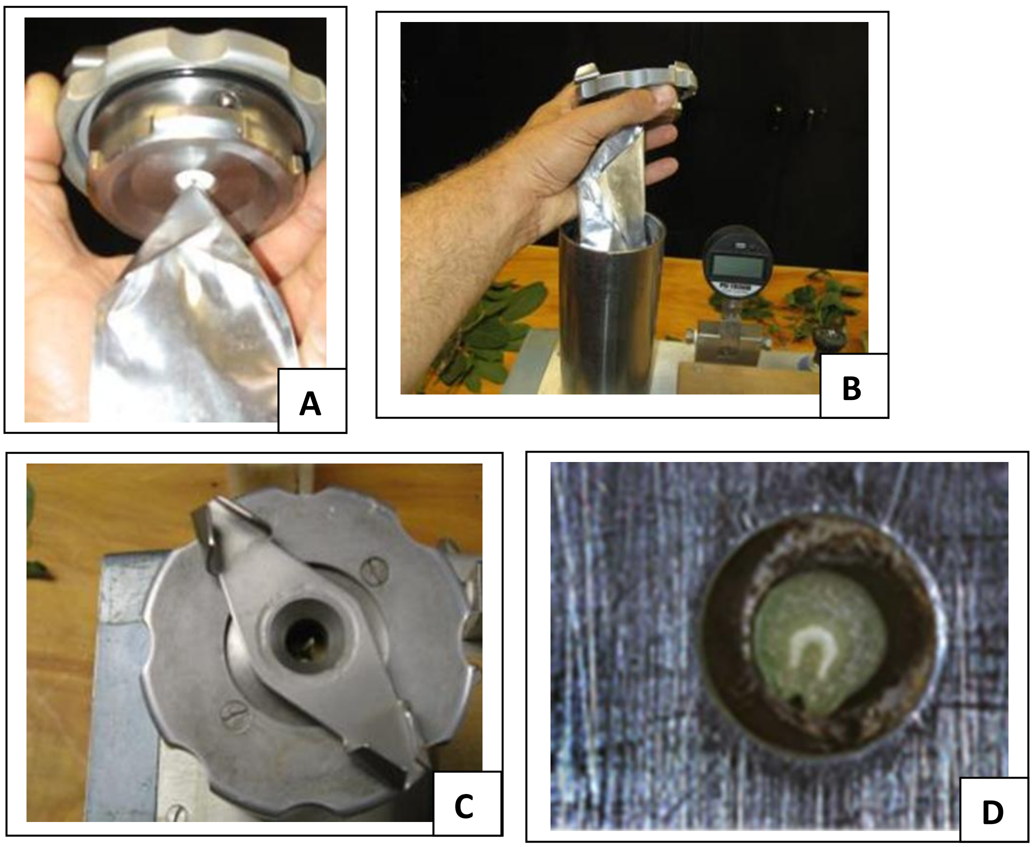


**Figure 5**. Basic process of measuring midday SWP with a pressure chamber. Photos: A. Fulton and K. Shackel.

Most pressure chambers (excluding hand-held pump-up models) incorporate an adjustable metering valve to regulate how fast pressure builds inside the chamber. Metering valves should be set to increase pressure slowly to lessen the chance of missing the endpoint. Operators should set the rate the chamber pressurizes slow enough so that it is possible to both watch for the endpoint and read the pressure gauge at the same time (fig. 6). Experience suggests that a pressure increase of 0.25 to 0.5 bars per second is just about right. When tree water status is at low to mild levels, pressure increases might be lower. Whereas, when tree water status is at moderate and higher levels, pressure increases may need to be higher to expedite measurements. In addition, less error occurs when pressure entering the chamber is quickly stopped at the endpoint by using the shut-off valve (NOT the regulator valve). The pressure regulator valve is a needle type that can be easily damaged from overtightening to stop pressure into the chamber.

SWP measurements should be completed as rapidly as possible after bagged leaves are excised. It usually takes an experienced operator 15 to 30 seconds to take a measurement depending on the plant water status. To minimize variability, readings should be made within 1 minute of being removed from the tree.


**Figure 6**. Photo of actual SWP measurement in walnut using a pressure chamber with digital gauge. Plant water status of this walnut tree was -5.67 bars tension. In this example, the length of stem protruding out of the chamber is about ½ inch to help show the end point in this picture. Ideally, the stem should not exceed 1/8 to ¼ inch. Photo: C. Haynes.

## *Interpreting SWP measurements*

### Baseline concept to distinguish weather from irrigation effects

Because SWP is affected by weather conditions at the time measurements are made, readings can vary from one day to the next as the weather changes, even if irrigation management and soil moisture are relatively stable. This has led to the development of the baseline concept for irrigation managers who want to improve upon their interpretation of SWP readings for irrigation scheduling.

The fully irrigated baseline SWP for any given day and time is defined as the SWP that is expected if soil moisture is abundant and not limiting transpiration under the prevailing temperature and humidity conditions.  Baseline may or may not vary with crop species.  For example, baseline conditions for almond and prune are very similar but are different for walnut. Baseline values are derived from mathematical models and have been validated in field experiments in almond, prune, and walnut.

Estimates of fully irrigated baseline SWP for almond and prune over a range of air temperatures and relative humidity are provided in table 1. Estimates of a fully irrigated baseline SWP for walnut are provided in table 2. During cool weather, estimates of baseline SWP may be –5 to –8 bars in almond and prune. However, under extremely hot and dry conditions, baseline SWP for almond and prune may be –11 to nearly -14 bars.  In walnut, estimates of baseline SWP may be -3 to -5 bars during cool weather and -6.5 to near -8 bars during extremely hot, dry weather.

Table 1.  Baseline SWP (bars) to expect for fully irrigated almonds or prune trees under different conditions of air temperature and relative humidity.

| **Tempera-ture (°F)** | **Air relative humidity (RH, %)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **10** | **20** | **30** | **40** | **50** | **60** | **70** |
| **75** | -7.3 | -7.0 | -6.6 | -6.2 | -5.9 | -5.5 | -5.2 |
| **80** | -7.9 | -7.5 | -7.0 | -6.6 | -6.2 | -5.8 | -5.4 |
| **85** | -8.5 | -8.1 | -7.6 | -7.1 | -6.6 | -6.1 | -5.6 |
| **90** | -9.3 | -8.7 | -8.2 | -7.6 | -7.0 | -6.4 | -5.8 |
| **95** | -10.2 | -9.5 | -8.8 | -8.2 | -7.5 | -6.8 | -6.1 |
| **100** | -11.2 | -10.4 | -9.6 | -8.8 | -8.0 | -7.2 | -6.5 |
| **105** | -12.3 | -11.4 | -10.5 | -9.6 | -8.7 | -7.8 | -6.8 |
| **110** | -13.6 | -12.6 | -11.5 | -10.4 | -9.4 | -8.3 | -7.3 |
| **115** | -15.1 | -13.9 | -12.6 | -11.4 | -10.2 | -9.0 | -7.8 |

Table 2.  Baseline SWP (bars) to expect for fully irrigated walnut trees under different conditions of air temperature and relative humidity.

| **Tempera-ture (°F)** | **Air relative humidity (RH, %)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **10** | **20** | **30** | **40** | **50** | **60** | **70** |
| **75** | -4.5 | -4.3 | -4.2 | -4.0 | -3.8 | -3.6 | -3.4 |
| **80** | -4.8 | -4.6 | -4.3 | -4.1 | -3.9 | -3.7 | -3.5 |
| **85** | -5.2 | -5.0 | -4.7 | -4.4 | -4.1 | -3.9 | -3.6 |
| **90** | -5.6 | -5.2 | -4.9 | -4.6 | -4.3 | -4.0 | -3.7 |
| **95** | -6.0 | -5.7 | -5.3 | -5.0 | -4.6 | -4.3 | -3.9 |
| **100** | -6.5 | -6.1 | -5.7 | -5.3 | -4.9 | -4.5 | -4.0 |
| **105** | -7.2 | -6.7 | -6.2 | -5.7 | -5.2 | -4.8 | -4.3 |
| **110** | -7.8 | -7.3 | -6.7 | -6.2 | -5.6 | -5.0 | -4.5 |
| **115** | -8.7 | -8.0 | -7.4 | -6.7 | -6.0 | -5.4 | -4.8 |

Estimating baseline conditions requires access to public or private weather databases (e.g., CIMIS) that provide hourly temperature and relative humidity data, or an inexpensive, simple handheld instrument that can measure temperature and relative humidity in the orchard at the same time that SWP measurements are taken.

An online calculator of baseline SWP is also available through the Fruit and Nut Research and Information Center: informatics. plantsciences.ucdavis.edu/Brooke_Jacobs/index.php. Alternatively, go to the Fruit and Nut Center website (fruitsandnuts.ucdavis.edu), go to the "Weather Related Models" tab and select "Stem Water Potential".

Comparing orchard SWP measurements to fully irrigated baseline SWP estimates allows you to express your orchard's SWP in bars below baseline. An example would be a day when weather is normal, the almond baseline is –10 bars and the orchard SWP measurements average –14 bars, or 4 bars below baseline. This suggests that tree water stress is occurring and that the need for irrigation is approaching. In contrast, on a different but very hot, windy day in the same almond orchard, when the baseline is –13 bars SWP and the orchard measurement averages -14 bars or just 1 bar below baseline, it suggests these readings are more associated with hot, dry weather conditions than with irrigation management. Once the hot, dry weather passes, both the estimate of baseline SWP and the orchard SWP measurements may recover to levels indicating lower tree stress. This information could guard against irrigating too soon or too much and help manage incidences of root and foliar diseases and improve access into the orchard for other activities.

Other potential benefits of comparing fully irrigated baseline to the actual SWP measurements include identifying orchards that are steadily near or above the fully irrigated baseline the entire season. These orchards may be at more risk of eventual tree loss from excess water and resulting diseases. Comparisons between baseline and actual SWP measurements can also be helpful to dial-in regulated deficit irrigation strategies to better manage uniformity of crop development and maturation. Examples include more uniform hull split and harvest timing in almond and higher sugar content and lower "dry-away" in prune. Using baseline estimates may also enable earlier use of a pressure chamber and SWP in the spring when weather is more variable.

## Interpretive guidelines for almond, prune, and walnut

Additional interpretive guidelines are provided in Tables 3, 4, and 5, for almond, prune, and walnut, respectively. They show that the ranges in SWP for almond and prune are similar up to a point. Almond may be able to survive more extreme levels of water stress than prune. However, research has not been conducted in prune to quantify how extreme water stress can become before mature trees no longer survive. Research has shown that walnut has a distinctly different range in water stress than almond or prune.

In general, UC production research has shown the optimum range in crop water stress levels of about -6 to -18 bars for almond, -6 to -20 bars for prune, and -4 to -8 bars for walnut. Some production research indicates that exceptional production may be possible when irrigation is managed to maintain tree water status to minimize or completely avoid SWP stress levels for the entire season. However, university experiments and production experience supporting intensive irrigation management that sustains orchards near baseline and minimal tree stress throughout the season is not conclusive. Concern exists about higher incidence of root and foliar diseases, lower limb shading and dieback, and shortened orchard life. Orchards, where SWP fluctuates more within these optimum ranges may still yield competitively but incur less tree loss and produce longer.

SWP is a field diagnostic tool that can help growers and consultants understand short and long term trends in orchard water status. With this knowledge they can tailor their management to achieve specific objectives and goals which may be different between orchards due to different growing environments and orchard designs (i.e. cultivar and rootstock choices, planting configurations, and pruning practices). The pressure chamber and SWP may also assist with minimizing the impacts of short water supplies during drought and balance water and energy costs.

Table 3. SWP levels in almond, consideration of how SWP might compare to baseline values under typical weather conditions, and the corresponding water stress symptoms to expect.

| SWP range (bars) | General Stress Level | Baseline consideration | Water stress symptoms in almond |
|---|---|---|---|
| -2 to -6 | None | (Likely above typical baseline) | (Not commonly observed) |
| -6 to -10 | Minimal | At or within 2 bars below baseline under normal conditions | Typical from leaf-out through mid-June. Stimulates shoot growth, especially in developing orchards. Higher yield potential may be possible if these levels are sustained (if the only limiting factor). Sustaining these levels may result in higher incidence of disease and reduced life span. |
| -10 to -12 | Mild | Near baseline under hot, dry conditions, but 2 to 4 bars below baseline under normal or cooler weather | These levels of stress may be appropriate during the phase of growth just before the onset of hull split (late June). |
| -12 to -14 | Mild to Moderate | Within 2 bars below baseline under hot, dry conditions, and 4 to 6 bars below baseline under normal or cool conditions | Reduced growth in young trees and shoot extension in mature trees. Suitable in late June up to the onset of hull split (July). Still produce competitively. Recommended level after harvest. May reduce energy costs or help cope with drought conditions. |
| -14 to -18 | Moderate to High | Likely 4 to 5 bars below baseline under hot, dry conditions and 6 to 8 bars below baseline in normal or cooler weather. | Stops shoot growth in young orchards. Mature almonds can tolerate this level during hull split (July) and still yield competitively. May help control diseases such as hull rot and alternaria leaf spot, if present. May expedite hull split and lead to more uniform nut maturity. Also may help reduce energy costs and cope with drought conditions. |
| -18 to -22 | High | Within 8 to 14 bars below baseline | Slow to no growth in mature orchards. Interior leaf yellowing with some leaf drop. Should be avoided for extended periods. Likely to reduce yield potential. |
| -22 to -30 | Very High | Within 14 to 24 bars below baseline | Wilting observed. Stomatal conductance of $CO_2$ and photosynthesis declines as much as 50% and impacts yield potential. Some limb dieback. |
| -30 to -60 | Severe | Within 24 to 50 bars below baseline | Extensive or complete defoliation is common. Trees may survive despite severe defoliation. Severely reduced or no bloom and very low yield expected following one to two seasons until trees are rejuvenated. |
| Below -60 bars | Extreme | (Substantially below baseline under all conditions) | (Trees are probably dead or dying) |

Table 4. SWP levels in prune, consideration of how SWP might compare to baseline values under various weather conditions, and the corresponding water stress symptoms to expect.

| SWP range (bars) | General Stress Level | Baseline consideration | Water stress symptoms in prune |
|---|---|---|---|
| -2 to -6 | None | (Likely above typical baseline) | (Not commonly observed) |
| -6 to -8 | Minimal | At or near baseline under normal or cool weather conditions | Typical in March and April. Indicates soil moisture is not limiting. If sustained, higher incidence of root and foliar diseases and tree loss may occur. |
| -8 to -12 | Minimal to Mild | At or near baseline under hot, dry conditions, but may be 2 to 4 bars below baseline under normal or cool conditions | Favors rapid shoot growth and fruit sizing in orchards when minimal crop stress is sustained from April through mid-June. |
| -12 to -16 | Mild to Moderate | May be 2 to 4 bars below baseline under hot, dry conditions, but may be 4 to 6 bars below baseline under normal or cooler weather | Suggested mild levels of stress during late June, July, and early August. Shoot growth slowed but fruit sizing unaffected. May help manage energy and irrigation costs. |
| -16 to -20 | Moderate to High | Within 6 to 8 bars below baseline | Should be avoided until fruit sizing is completed. Appropriate for late August after fruit sizing is completed. Imposing moderate to high levels of crop stress by reducing irrigation about two weeks before harvest may increase sugar content in fruit and reduce moisture content or “dry-away” (fruit drying costs). |
| -20 to -30 | High to Severe | Within 8 to 20 bars below baseline | More likely to occur in late August and early September during and after harvest. Extended periods of high crop stress before harvest will result in defoliation and exposure of limbs and fruit to sunburn. Extended periods of high stress after harvest may also negatively affect the condition of trees going into dormancy. |
| Below -30 | Extreme | (Substantially below baseline under all conditions) | Extended periods of severe crop stress should be avoided. Trees will defoliate and be exposed to sunburn, increasing the risk of canker diseases. Potentially shorten productive life of orchard. |

Table 5. SWP levels in walnut, consideration of how SWP might compare to baseline values under various weather conditions, and the corresponding water stress symptoms to expect.

| SWP range (bars) | General Stress Level | Baseline consideration | Water stress symptoms in walnut |
|---|---|---|---|
| Higher than –2 | None | (Likely above typical baseline) | (Not commonly observed) |
| -2 to –4 | None | At or above typical baseline | Fully irrigated. Commonly observed when orchards are irrigated according to estimates of real-time evapotranspiration ($ET_c$). If sustained, long term root and tree health may be a concern, especially on California Black rootstock |
| -4 to –6 | Minimal | May equal or be as much as 2 bars below typical baseline | High rate of shoot growth visible, suggested level from leaf-out until mid-June when nut sizing is completed |
| -6 to –8 | Mild | May equal baseline under hot, dry conditions, but may be 2 to 4 bars below baseline under normal or cooler weather | Shoot growth in non-bearing 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 1 to 2 bars below baseline under hot, dry conditions but 4 to 6 bars below baseline under normal or cooler weather | Shoot growth in non-bearing 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 | Likely 3 to 4 bars below baseline under hot, dry conditions and 6 to 8 bars below baseline in normal or cooler weather. | 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 | Likely 5 to 6 bars below baseline under hot, dry conditions and 8 to 10 bars below baseline in normal or cooler weather. | Results in moderate defoliation. Should be avoided. |
| -14 to –18 | Severe | Likely 7 to 8 bars below baseline under hot, dry conditions and 10 to 12 bars below baseline in normal or cooler weather. | Severe defoliation, trees are likely dying. |
| Below -18 | Extreme | (Substantially below baseline under all conditions) | (Trees are probably dead or dying) |

## Using SWP in other crops

A grower or consultant who invests in a pressure chamber may be interested in its application in other crops. Research and development of the pressure chamber to evaluate crop water stress and help with on-farm water management has been undertaken in several crops for many decades. It's readiness for on-farm use varies among crops. Cotton and wine grapes are examples of crops where an abundance of research has been conducted and information extended so the pressure chamber is available as a water management tool. However, in both of these crops the measurement technique differs from SWP. In these crops with smaller canopies, the sample leaf is not covered with a bag and leaf water potential is measured not SWP.

In crops such as olive, pistachio, peach, pecan, seed alfalfa, and others there is limited information available. The information may originate both from California and other areas of the U.S. and internationally and may involve different sampling techniques other than SWP such as leaf water potential and shaded leaf water potential. If interested in any of these crops, one suggested source to begin a literature search is: https://www.pmsinstrument.com/research/.

### *A Stand-Alone or Complementary Irrigation Management Tool*

As a direct measure of tree response to irrigation management and the soil, climate, and orchard environment, SWP is unique compared with other methods that assess tree water status indirectly. As such, through trial and error, SWP can be used—and has been successfully adopted by many growers—as a stand-alone technique for irrigation scheduling. Using SWP alone, along with the interpretive guidelines presented in this article, gives relatively straightforward insights to the question of when to irrigate and with experience, perhaps how long to irrigate.

However, trial and error may not suffice in some situations, and SWP measurements alone may not provide enough information. For example, pressure chamber measurements can show low crop stress in April, May, and early June in orchards, even though irrigation has been postponed or reduced. The trees consume water stored in the root zone from winter rainfall or winter irrigation during this period to satisfy their water requirements. Without some monitoring of soil moisture or tracking of ET, it is possible to experience a sudden and rapid increase in tree water stress in July, August, and September. Meanwhile, a drip or microsprinkler irrigation system will not have the capacity to apply enough water to recharge the soil moisture depletion and sufficiently relieve tree stress. This can be a problem particularly in orchards where soils have slow water infiltration. Irrigation should be initiated before the stored water is depleted excessively.

Using SWP in conjunction with soil moisture monitoring or a water budget (or both) can also help overcome some common limitations of soil moisture monitoring and irrigating according to ET. SWP readings that indicate low tree stress, even though soil moisture sensors indicate dry soil, might suggest that trees are getting water from greater depths in the root zone that are not being monitored by soil moisture sensors. This situation could indicate a need for deeper soil moisture monitoring or placing soil moisture sensors in more representative locations. Similarly, SWP readings that indicate desirable levels of tree stress, even when a water budget indicates under-irrigation, suggest the need to reexamine assumptions about ET rates, rooting depth, and available moisture reserves.

In a different situation, SWP measurements might indicate moderate to high tree stress even when soil moisture sensors placed within the wetted pattern of the drip emitter show high soil moisture content. In this case, additional investigation is necessary to determine if roots are healthy and growing, and if the soil moisture sensors accurately represent the root zone and predominant soil types or if the sensors are defective.

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