# A Leaf Monitoring System for Continuous Measurement of Plant Water Status to Assist in Irrigation Management of Specialty Crops

**Project No.:** **17-HORT24-Upadhyaya**

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## Objectives:

The specific objectives of this study are to (i) quantify the benefits of a plant water stress based site-specific irrigation management scheme that employs a wireless mesh network for almond crop in comparison to ET based irrigation management schemes, and (ii) demonstrate the technology to growers. While the soil moisture content will be monitored, the continuous leaf monitoring system developed at UC Davis that detects the plant water status in real-time will be the key sensor used for decision making and precision irrigation management.

## Interpretive Summary:

Precision irrigation techniques can help ensure that the necessary amount of water reaches the roots of the right tree at the right time in the drought-prone climate of California's Central Valley. To achieve this goal, a leaf monitor was developed which measures leaf temperature and other microclimatic variables (air temperature, relative humidity, light, and wind speed) necessary to estimate Plant Water Status (PWS). During the 2017 growing season, the leaf monitor design was further improved by adding a second IR sensor to measure the dry leaf temperature within the same dome. Moreover, specially developed spacers were incorporated into the design to position the IR sensors at a precise distance from the leaf surface and ensure the IR sensor field of view was completely within the leaf surface, which is particularly important for almond leaves that tend to be small. Leaf monitors were interconnected in a 4-acre almond orchard at Nickels Soil Lab through a wireless mesh network to implement precision irrigation during the 2016 and 2017 growing seasons. Irrigation was scheduled independently in two management zones, which were created from evaluation of soil and plant characteristics. CWSI values were calculated using a saturated reference tree that received 50% more water and a dry reference, simulated by a leaf with a broken stem. CWSI values were continuously used to guide irrigation decisions in each zone during the 2016 season and a new PWS indicator known as Comprehensive Stress Ratio (CSR) was used during the 2017 season to achieve a targeted stress level which varied based on fruit development stage. Midday measurements of stem water potential were obtained to validate irrigation decisions.

When the average stress of a managed zone exceeded allowable levels, irrigation was implemented at a defined percentage of estimated evapotranspiration. This percentage was adjusted until the desired stress level was achieved at regular time intervals. This PWS based irrigation scheme required 30% less water compared to ET based irrigation and 17% less water compared to grower-based irrigation scheme that utilized soil moisture sensors without causing a significant reduction in yield or quality. These results suggest this method of precision irrigation may be a useful tool for irrigation scheduling and increased water savings in almonds.

## Materials and Methods:

In the 2017 growing season, variable rate, deficit irrigation based on a continuous, proximal leaf monitoring system was implemented in a 4-acre plot of almond crop at Nickels Soil Laboratory in Arbuckle, California as was done during the 2016 growing season. The study was conducted on Nonpareil almond rows, which were adjacent to two rows of pollinator varieties on either side. This plot was divided into management zones based on the soil and plant characteristics of digital elevation, shallow EC, soil texture, leaf temperature, and canopy cover (**Figure 1**). Two management zones were created from these characteristics using unsupervised fuzzy classification included in USDA’s Management Zone Analyzer software as shown in (**Figure 1)**.

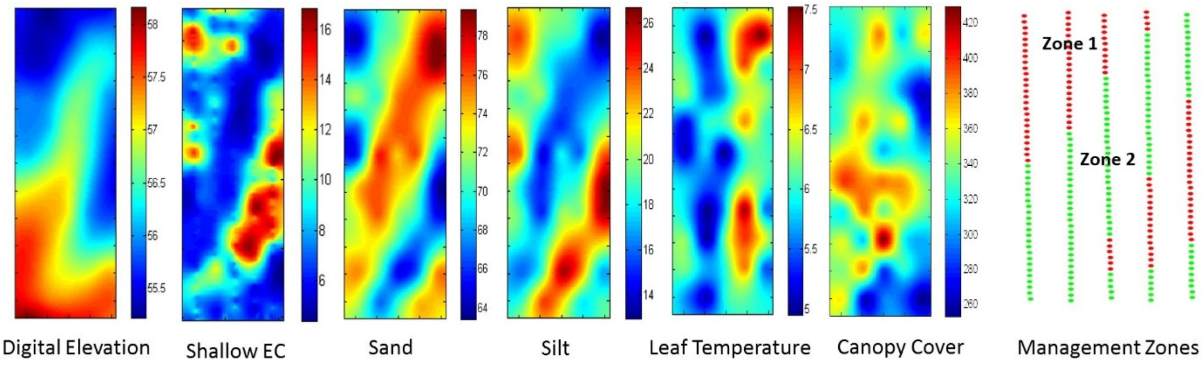

**Figure 1.** Management zone development based on plant and soil characteristics. From left to right: digital elevation, shallow EC, sand content, silt content, leaf temperature, canopy cover, and final determination of management zones. In the final management zones, each dot represents a tree in the orchard. Figures reproduced from (Kizer, 2018).

Two irrigation treatments were implemented. Two rows of the orchard were controlled by traditional grower management. Two other rows in the plot received the stress-based treatment. The fifth row was dedicated to testing the performance of the second IR sensor that was added to the leaf monitor during the 2017 growing season. In the grower treatment, irrigation decisions were made using three Watermark sensors installed at three different depths at one location to check for soil moisture depletion and water was applied uniformly across both management zones. In stress-based treatment, the necessary amount of water to achieve a targeted plant water status (PWS) was applied to each management zone independently. Drip irrigation lines were adjusted to align with each management zone in the stress-based irrigation treatment rows. Similar to the procedure used in previous seasons, leaf monitors, soil moisture sensors, pressure sensors, flowmeters, and latching solenoid valves

were interfaced to Eko Pro Wireless Sensor Nodes. Leaf monitors used a RS485 chip on a custom printed circuit board. Leaf monitor data was sampled every 4 minutes and transmitted at 15-minute intervals. Irrigation was controlled separately for each treatment zone via the web using individual latching solenoid valves. Eko Nodes transmitted data to a gateway computer which uploaded them to the web. Repeaters were used to increase the range of the radio signal so that it reached the fieldhouse where the gateway computer was located.
A total of 12 leaf monitors were installed to monitor treatments, with 3 leaf monitors in each treatment zone to provide a representative average for PWS in that zone. One additional leaf monitor was installed to monitor a tree which received 50% more water for each irrigation to simulate the saturated condition. The dry leaf temperature was obtained using the second IR sensor included within the dome. These data permitted the calculation of a crop water stress index (CWSI) ranging from zero to one, where a value of zero indicated a tree with no water stress (Jackson et al., 1981; Jackson et al., 1988). CWSI was defined as in Equation 1,

$$CWSI = \frac{\left(T_{leaf} - T_{air}\right)_{observed} - \left(T_{leaf} - T_{air}\right)_{sat}}{\left(T_{leaf} - T_{air}\right)_{dry} - \left(T_{leaf} - T_{air}\right)_{sat}} \qquad (1)$$

where T is temperature and subscript ‘sat’ stands for saturated, ‘dry’ stands for simulated dry leaf, ‘observed’ stands for monitored leaf, ‘leaf’ stands for leaf temperature, and ‘air’ stands for air temperature. A new dynamic stress indicator that eliminated the need to maintain a separate saturated tree, which may not undergo similar acclimatization as the monitored tree, was developed based on an energy balance principle on a leaf (Kizer, 2018). This new stress indicator was termed “Comprehensive Stress Ratio (CSR)” and is given by:

$$CSR = \frac{T_L^{Dry} - T_L^M}{\mathrm{e}_{sat}(T_L^M) - \mathrm{e}(T_A)} \qquad (2)$$

where $T_L^{Dry}$ is the simulated dry leaf temperature, $T_L^M$ is the monitored leaf temperature, $T_A$ is the air temperature, e is the vapor pressure of water vapor, and subscript sat stands for saturated condition.

Each day CWSI/CSR values were evaluated from data obtained and averaged between 12:00 and 16:00 h. Irrigation decisions in the stress-based treatment were made based on changing CWSI/CSR values. Deficit irrigation amount was started at 85% and 90% of $ET_c$ for management zones 1 and 2, respectively, reflective of the water requirements of each management zone from the previous years. $ET_c$ was calculated by the Penman-Monteith method with crop coefficient values and with California Irrigation Management Information System (CIMIS) weather data. The aim was to achieve the desired stress or CWSI/CSR value for a given fruit development stage by scheduling the irrigation at the right time. The strategy of decreasing or increasing water applied in 5% increments of $ET_c$ on the third day after irrigation was followed in the beginning of the season. As the season progressed, a slightly different approach was used which eliminated the reliance on a saturated tree and targeted the desired stress level– usually by delaying the irrigation rather than implementing the conventional practice of irrigating every third day. The targeted stress levels for almond trees during the 2017 growing season were -12 to -14 bars pre- and post- hull-split periods and -14 to -18 bars during the hull-split period.

Flow meter readings were recorded after each irrigation event to obtain the actual amount of water applied to each treatment during each irrigation during the entire growing season. SWP measurements were taken three times a week to ensure that the leaf monitor based variable rate irrigation maintained the SWP values within the desired range. Yield data were obtained for each treatment zone using a weigh wagon. Quality analysis of kernel size, mold percentage, and kernel mass were performed on almonds sampled from both grower and stress-based treatments.

## Results and Discussion:

During the 2017 growing season, we implemented precision irrigation for the whole growing season starting from May 8th until harvest, August 17th. All irrigation decisions were made using the CWSI/CSR information derived from the leaf monitors. However, SWP readings were taken at regular intervals (three times a week) to make sure that the trees remained in the expected stress range. While we tried to use CWSI values to manage irrigations, we noticed an unexplained shift in the CWSI values around July 15th, most likely due to acclimatization. While the trees that were stressed tended to acclimatize to the environmental conditions, the saturated tree did not appear to go through this process to the same extent. Since saturated tree leaf temperature is involved in computing CWSI as shown in equation (1), the only way to account for this type of change would be through frequent recalibration, which is neither desirable nor practical. So, we developed an alternate technique that eliminated the need for saturated leaf temperature. We decided to use CSR given in equation (2) that utilizes the monitored and dry leaf temperatures, air temperature, and RH data. Sample plots of CSR data for three leaf monitors in management zone #2 are shown in (**Figure 2)**. All these plots start from an irrigation event day shown by blue triangles. CSR is low, particularly in afternoon hours on this day. Aqua circles show the recovery one day after irrigation. On the following day (two days after irrigation) there is further recovery (green circles). Third day after irrigation (yellow triangles) show a decrease in afternoon CSR values, indicating that it is time to irrigate again. A similar pattern starts after the second irrigation. This pattern was used to implement precision irrigation in each zone throughout the rest of the season. While this relative behavior was very useful to make irrigation decisions, the magnitudes of CSR values depended on the leaf selected (i.e., leaf specific). We are trying to develop a leaf independent index from these CSR values. However, the pattern is very clear and has been helpful to manage irrigation while maintaining stress in the desired range. The measured SWP values using a pressure chamber are presented in (**Figure 3)**. The stress values generally follow the desired pattern except following the hull-split period, around the time the harvest preparations started.

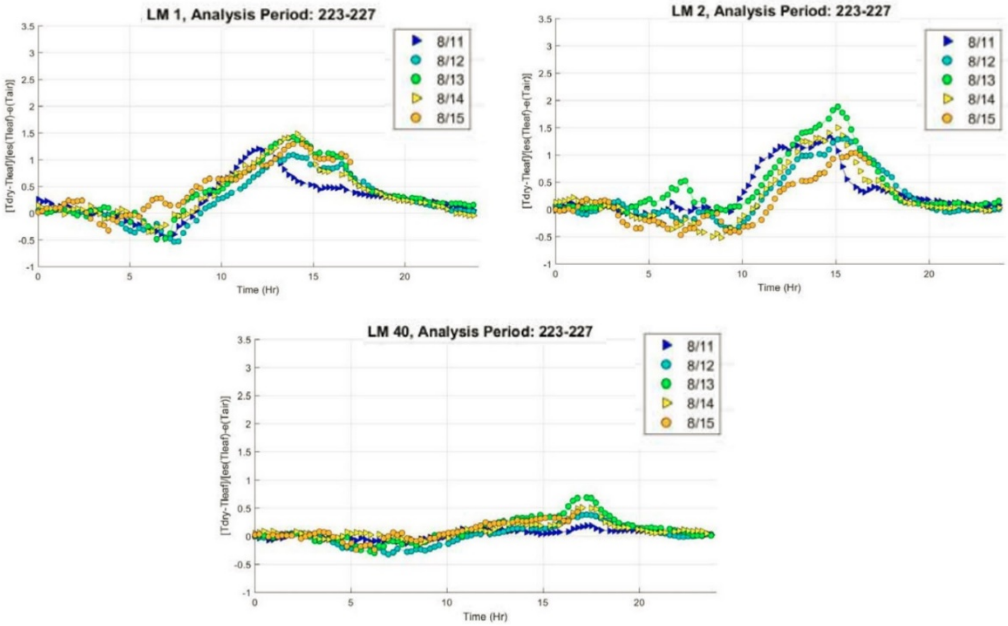

**Figure 2**. CSR plots for stress-based treatment in management zone 2 in the 2017 season.

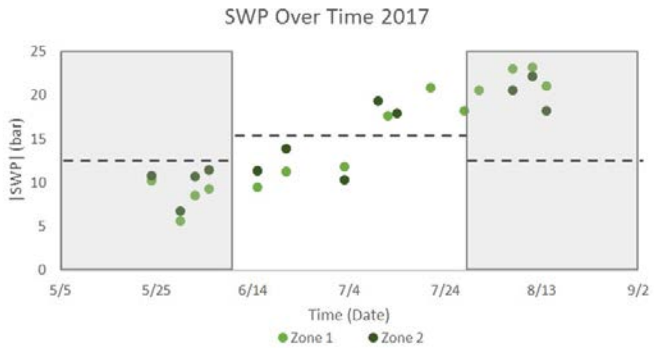

**Figure 3.** Stress plots before, during and after hull split from SWP measurements taken the day of irrigation in the 2017 season. Note SWP values are inverted to the positive for ease of interpretation**.**

Cumulative water use, water productivity, yield, and quality data were analyzed. Cumulative water use data for the 2017 growing season is shown in (**Figure 4)**. Amount of water applied tended to be similar in the beginning of the season. However, amount of water applied by the grower, which is based on soil moisture sensing at a selected location, increased beyond the stress-based treatments considerably as season progressed. Essentially, the grower treatment resulted in the greatest water applied followed by stress-based treatment in zone 2. The stress-based treatment in zone 1 required the least amount of water applied. The data for both growing seasons (2016 and 2017) were pooled and statistical analysis was conducted to determine the effect of stress-based irrigation compared to the grower practice. (**Table 1)** lists the water productivity and amount of water applied for different treatments. Stress based treatments required significantly less water ($p<0.0001$) and water productivity corresponding to the stress-based treatment was significantly higher ($p=0.0057$).

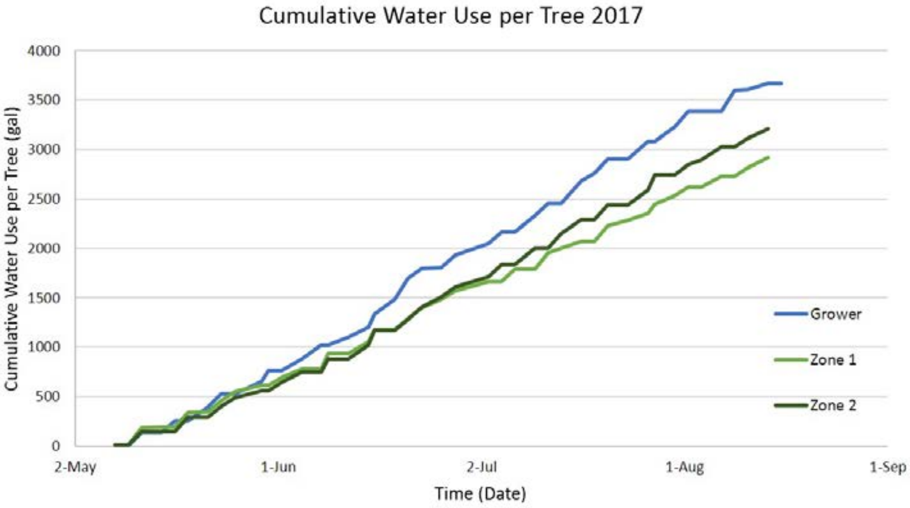

**Figure 4.** Cumulative water uses per tree for the 2017 growing season for grower (blue), stress-based zone 1 (light green), and stress-based zone 2 (dark green) treatments where Zone 2 water use was based only on one replicate.

**Table 1.** Average water productivity (lb./acre) and average water applied (gal/tree) for 2016 & 2017 seasons.

| Treatment | Zone | Average Water Productivity (lb/acre-ft) | Average Water Applied (gal/tree) |
|---|---|---|---|
| Stress | 1 | 2157 ± 359 | 2922 ± 40 |
| Stress | 2 | 2051 ± 267 | 2907 ± 261 |
| Grower | 1 | 1816 ± 203 | 3512 ± 184 |
| Grower | 2 | 1933 ± 185 | 3512 ± 184 |

(**Figure 5**) is a summary bar chart of average water applied per tree over the two-year period compared to CIMIS derived ET requirements. This figure shows that while soil moisture-based grower practice reduced water requirements compared to CIMIS estimated ET requirements, plant water stress-based treatments further decreased water requirements compared to grower practice.

(**Table 2**) presents the effect of different treatments on crop yield.  While there was no significant difference between grower practice and stress-based treatment, grower treatment resulted in higher yield in zone 2.

**(Table 3)** displays the various quality parameters investigated in this study (kernel mass, length, width and thickness, and number of moldy kernels in 50 kernels).  None of these quality parameters were found to be significantly different between stress-based irrigation treatment and grower practice.

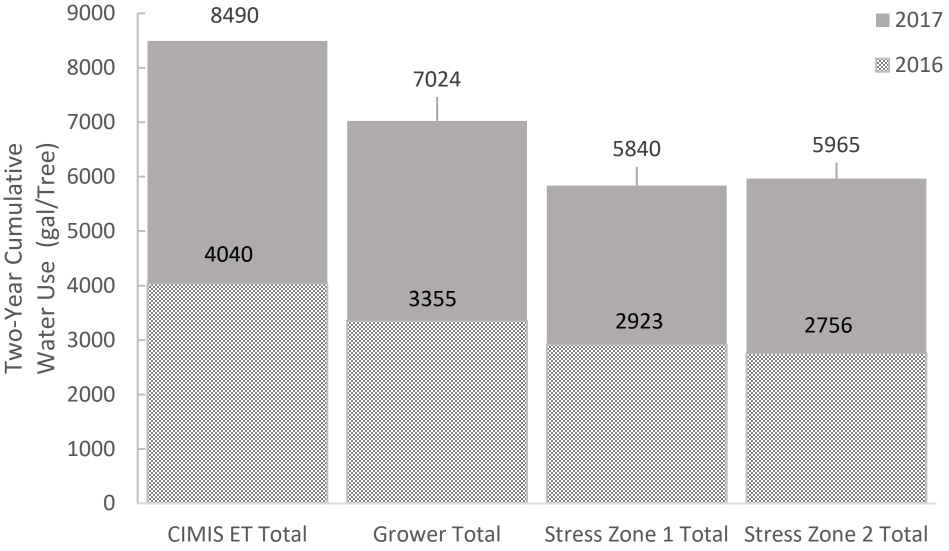

**Figure 5.** Total water uses per tree for CIMIS evapotranspiration (ET) estimates, for grower treatment, and for stress-based zone 1 and zone 2 treatments for the 2016 & 2017 growing seasons.

**Table 2.** Average raw yield, normalized raw yield, and kernel yield for the 2016 & 2017 growing seasons. Normalized data is compared to the raw yield of the 2015 growing season.

| Treatment | Zone | Raw Yield (lb/acre) | Kernel Yield (lb/acre) |
|---|---|---|---|
| Stress | 1 | 11704 ± 1103 | 3010 ± 500 |
| Stress | 2 | 11439 ± 1383 | 2860 ± 610 |
| Grower | 1 | 11581 ± 1255 | 3060 ± 490 |
| Grower | 2 | 12158 ± 719 | 3250 ± 460 |

**Table 3.** Quality data averages for yield from 2016 & 2017 growing seasons. Numbers reported are based on samples of 50 kernels, except for kernel dimensions, which are based on a sample of 10 kernels.

| Treatment | Zone | Average Kernel Mass (g) | Length (mm) | Width (mm) | Thickness (mm) | Number of Moldy Kernels in 50 |
|---|---|---|---|---|---|---|
| Stress | 1 | 1.31 ± 0.03 | 24.8 ± 0.9 | 13.5 ± 0.3 | 8.5 ± 0.3 | 12 ± 6 |
| Stress | 2 | 1.33 ± 0.01 | 24.2 ± 0.4 | 13.8 ± 0.2 | 8.4 ± 0.3 | 16 ± 5 |
| Grower | 1 | 1.33 ± 0.04 | 24.1 ± 0.4 | 13.6 ± 0.3 | 8.4 ± 0.1 | 13 ± 7 |
| Grower | 2 | 1.33 ± 0.04 | 24.4 ± 0.4 | 13.6 ± 0.2 | 8.4 ± 0.2 | 19 ± 6 |

Results of this study suggest that precision irrigation that monitors plant water status using continuous leaf monitors may be useful for irrigation scheduling and enhancing water savings in almond crop.

## Research Effort Recent Publications:

Kizer, E. 2018. A precision irrigation scheme to manage plant water status using leaf monitors in almonds. Unpublished MS thesis. Bio and Agr Eng Dept., University of California Davis, Davis, CA 95616. 124pp.

Channing Ko-Madden. 2018. Optimal placement of minimal number of proximal sensors for precision irrigation management. Unpublished MS thesis. Bio and Agr Eng Dept., University of California Davis, Davis, CA 95616. 153pp.

Meyers, J. 2018. Development of an artificial neural network approach for predicting plant water status in almonds. Unpublished MS thesis. Bio and Agr Eng Dept., University of California Davis, Davis, CA 95616. 49pp.

Meyers, J., I. Kisekka, S. K. Upadhyaya and G. Michelon. 2018. Development of an artificial neural network approach for predicting plant water status in almonds. Manuscript submitted to the Transaction of ASABE. 19pp.

Dhilloon, R., F. Rojo., S. K. Upadhyaya, J. Roach, R. Coates, and M. Delwiche. 2018. Prediction of plant water status in almond and walnut trees using a continuous leaf monitoring system. Submitted to the Precision Ag Journal. 28pp.

Kizer, E., C. Ko-Madden, K. Drechsler, J. Meyers, C. Jiang, R. de S. Santos, and S. Upadhyaya. 2018. Precision irrigation in almonds based on plant water status. Technical note. Amazonian Journal of Plant Research. 2(1):113-116

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