DEVELOPMENT AND EVALUATION OF A LEAF MONITORING SYSTEM FOR CONTINUOUS MEASUREMENT OF PLANT WATER STATUS IN ALMOND AND WALNUT CROPS

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ABSTRACT

Almond and walnut are two major crops grown in the Central Valley of California. With virtually no rainfall in this area during summer, these crops need to be irrigated throughout the season. There is a demand for using irrigation scheduling tools for effective use of very limited supply of water. Leaf temperature measurement using infrared thermometers has been used to predict plant water stress or to develop different indices to quantify plant water stress, but mostly on field crops. There have been very few studies conducted on tree crops. In this study, an inexpensive, easy to use sensing system called a 'leaf monitor' was developed and evaluated to continuously measure leaf temperature and relevant microclimatic variables in the vicinity of a leaf for prediction of plant water status for tree crops. The system was installed on almond and walnut trees to continuously monitor a selected leaf on each tree by logging leaf temperature, air temperature, relative humidity, wind speed and Photosynthetically Active Radiation (PAR). This study also proposed a method to develop a modified crop water stress index (MCWSI) in which a well-watered baseline was developed after every irrigation event for each tree for incorporating any temporal variability throughout the season. Additional parameters measured by leaf monitor also assists in controlling levels of disturbance variables like wind speed and light conditions. Leaf monitors were installed as a part of a wireless mesh network in field conditions. Data were obtained remotely over the web, and daily MCWSI values were calculated by assigning first day after irrigation as the reference day. MCWSI values were found to be correlated well with measured plant water stress, as measured by stem water potential (SWP). Sensing system has potential to be used as irrigation scheduling tool as it was able to provide a daily stress index value which follows a similar pattern as the actual plant water stress.

Keywords: Leaf temperature, Irrigation scheduling, Continuous measurement, Wireless mesh network, Stem water potential, Stress index, Plant water status, Almonds, Walnuts, Nut crops

INTRODUCTION

Agriculture is an important component of California's economy with a value of more than 45 billion dollars. On the other hand, California is leading in withdrawing irrigation water, consuming more than one-fourth of total irrigation water withdrawn in the nation (USGS, 2005). However, California is suffering one of the worst drought conditions in history and farmers are allocated no or very little federal water in many irrigation districts for 2014. Recent drought situations, overall limited availability of irrigation water in California, and increasing urban demand are forcing agriculture to implement precision irrigation techniques to improve water use efficiency. It is very critical that irrigation needs to be managed based on crop needs. Irrigation scheduling techniques have been developed mostly based on soil moisture monitoring in past. It has been found that soil moisture measurements are influenced by position of soil moisture sensor in the root zone and do not represent water availability to plants in the whole root zone, especially in case of orchard crops. Therefore, plant's response to water stress is considered as a better indicator of plant water stress (PWS), as it responds to the integrated soil moisture status of the whole root zone (Jones, 2004). PWS measurements for orchard crops are usually obtained using a "pressure chamber" or "pressure bomb", which is considered as the standard method to measure mid-day stem water potential (SWP) for quantifying PWS (Boyer, 1967; Lampinen et al., 2001). However, mid-day SWP measurements using a pressure chamber are very time consuming, tedious and labor intensive which makes it impossible to obtain large number of samples necessary to develop efficient irrigation scheduling techniques.

Leaf or canopy temperature is a plant parameter mainly used to calculate Crop Water Stress Index (CWSI) to quantify plant water stress (Idso, 1981). CWSI is given by equation:

$$CWSI = \frac{\Delta T - \Delta T_{WWB}}{\Delta T_{FWSB} - \Delta T_{WWB}} \qquad [eq. 1]$$

where ΔT is the measured temperature difference between leaf and air temperature at any given time, ΔT_{WWB} is the temperature difference under well-watered conditions, and ΔT_{FWSB} is the temperature difference at fully water stressed condition. CWSI varies from 0 to 1 for well watered to completely stressed states of a tree. In-situ proximal canopy temperature measurements have been used successfully to measure and evaluate CWSI to predict plant water status for field crops using handheld IRT sensors (Yazar et al., 1999; Nielsen, 1994). CWSI has been also used to estimate yield of corn crop (Irmak et al., 2000). It has been found to be a sensitive indicator to water stress in orchard crops as well (Torman et al., 1986; Testi et al., 2008). However, Andrews et al. (1992)

did not find CWSI as a good predictor of plant water stress in apple trees. Moreover, CWSI was found to be not as sensitive to plant water stress in humid climates (Jones et al., 1997). It can also be sensitive to environmental factors like wind and PAR (Fuchs, 1990; Hipps et al., 1985).

In a recent study, leaf energy balance equation was used to predict leaf temperature as function of plant water status and microclimatic variables (Udompetaikul, 2012). These models were used to classify trees as water-stressed and not water-stressed (Udompetaikul, 2012; Dhillon et al., 2013). But these prediction models were found to change during the season, which suggests a need to measure leaf temperature and other environmental parameters multiple times during the season this may not be practical due to the labor involved in measurements. To overcome these issues, we developed a sensing system to continuously monitor plant water status and make that information available for irrigation management.

The specific objectives of this research were to:

I. Develop a "leaf monitor" for continuous measurements of leaf temperature, and other relevant microclimatic variables.
II. Test the performance of the leaf monitor in almond and walnut orchards.
III. Develop an indicator of Crop Water Stress using leaf monitor data for quantifying the daily PWS level of tree.
IV. Evaluate the performance of leaf monitor for estimating plant water status as compared to the conventional measurements in almond and walnut crops.

MATERIAL AND METHODS

Leaf monitor development

The leaf monitor is a sensor system which measured leaf temperature and relevant microclimatic parameters in the vicinity of a leaf on a continuous basis. This sensor system consisted of an infra-red thermometer (IRT) (Melexis MLX90614ESF-BCF-000-TU) to measure leaf temperature. This sensor had a measurement resolution of 0.01 ° C and accuracy of 0.5 °C and had an I^2C interface option and could operate on a 3 V or 5 V DC power supply. An integrated air temperature and relative humidity sensor (SHT25, Sensirion) to measure air temperature (band gap temperature sensor) and relative humidity (capacitance based humidity sensor) around the leaf were also included in the sensor system. These sensors consisted of 14-bit analog to digital convertor (ADC) and 2-wire I^2C protocol and had resolutions of 0.03% for RH and 0.01 °C for temperature. The corresponding tolerances were ±3% RH and less than ±0.5 °C for temperature. A low cost wind speed sensor was used to measure wind speed around the leaf. The wind sensor, designed by co-author Jed Roach, consisted of 2 thermistors in a Wheatstone bridge, an analog switch, and a MCP3424 ADC to measure the bridge voltage. This sensor was more sensitive at low wind speeds – a condition that exists around the leaf positioned in a dome in the leaf monitor because of the presence of a wind barrier around the leaf. An ambient light sensor (TSL2561T, AMS) to measure solar radiation on the leaf surface was also included. This sensor had 16-bit ADC and I^2C communication bus. The light sensor was calibrated using a PAR sensor (LI-190, LICOR Inc. Lincoln, NE).

These sensors were assembled on a custom printed circuit board along with an Arduino compatible microcontroller that could continuously monitor all the sensors at a desired sampling rate and report the data to a wireless node. In addition, the leaf monitor also consisted of a leaf holder. Leaf chosen on tree to make continuous leaf temperature measurements had to be fixed in front of the infrared sensor to make sure that the sensor was always pointed at the leaf surface. Leaf holder, basically consisted of mesh of nylon wire around two metal rings. The leaf was held between these two rings and the position of the rings could be adjusted according to leaf orientation. We found that at times surface of the leaf under observation received non-uniform solar radiation (i.e. sun flecks). A solar radiation diffuser dome was used to make sure that light sensor was exposed to the same light level as the leaf. This diffuser was a hemispherical, opaque plastic film which diffused direct sunlight flecks and made light conditions more uniform inside the dome. A wind barrier was installed to minimize the effect of wind speed on the transpiration of the leaf. A wind speed sensor was installed inside the wind barrier to verify its effectiveness. With this design, in which we attempted to have uniform light and virtually no wind conditions around the leaf, leaf temperature was expected to be less influenced by environmental conditions.

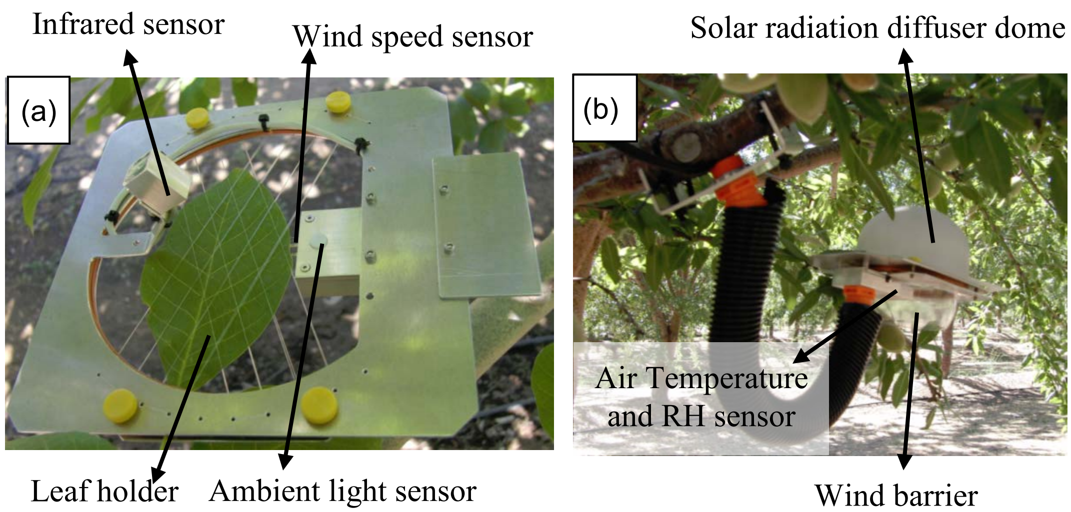


Figure 1: Leaf monitor installed on (a) walnut tree (picture taken before installing dome) and, (b) almond tree for field testing.

Data collection

For field testing, leaf monitors were installed on shaded leaves of Almond and Walnut trees (figure 1) at Nickel's Soil Lab, Arbuckle, CA. Leaf monitors were integrated into an existing wireless sensor network (Coates et al., 2013) at the field site for precision irrigation control using wireless eKo nodes. This wireless network was initially set up for remotely actuating latching solenoid valves based on different irrigation treatments to blocks of five trees. An RS485 module installed on the leaf monitor circuit board made it possible to communicate with eKo pro wireless sensor nodes (Memsic Inc., Andover, MA).

These nodes transmit the sensor data to an internet connected gateway computer and webserver, so that the data can be viewed from anywhere using a web browser. Nodes were also the source of input power to the leaf monitor unit. Five trees in each of 20 almond blocks and 16 walnut blocks were able to receive independent amount water through variable rate irrigation system. These blocks were grouped into three management zones of high, medium and low irrigation requirements. Three different irrigation treatments (100% evapotranspiration (ET) replacement, grower irrigation, and stress-based irrigation) were implemented in each zone. Stress based irrigation was controlled according to measured stress level of trees, water application was varied to target SWP values equal to the average measured SWP values of other two irrigation treatments. Overall, grower irrigation treatment applied 2.6 and 2.1 times of water used in ET based treatment in almonds and walnuts respectively and SWP based treatment applied ~1.5 times of water as compared to ET based treatment in both crops. Leaf monitor units were installed on a few randomly selected blocks in all three zones. Leaf monitor measured leaf temperature, air temperature, relative humidity, PAR and wind speed and this data packet along with board's unique serial number was sent to the network every 16 minutes starting from July to early October. These data were stored in a database on the gateway computer and were available to access in real-time from anywhere using the web. Actual plant water status was also measured as ground-truth data. Mid-day SWP values from tree on which leaf monitor was installed was measured using the standard "pressure chamber" after enclosing one shaded leaf per tree in a reflective plastic bag for at least 20-30 minutes.

Modified CWSI calculation

Preliminary data analysis indicated that the well-watered baseline tended to change from irrigation to irrigation (temporal variation). Therefore we decided to develop a modified crop water stress index (MCWSI) to properly account for this condition. Data were analyzed in the SAS software package (SAS Institute, Inc. v.9.3 Cary, NC). Data corresponding to 10:00AM to 4:00PM were selected and a moving average for four data points (one hour data) was used for smoothening. An index was calculated by developing well-watered and fully water-stressed baselines. Trees were irrigated at night and were considered well-watered one or two days later, as it was seen from pressure chamber data that some trees were taking two days to totally recover from water stress after irrigation. The purpose of developing a leaf monitor was to capture the temporal variation in leaf temperature in relation to plant water stress and environmental conditions. Therefore, we developed a stress index in which the well-watered baseline was updated after every irrigation event; this was called Modified Crop Water Stress Index (MCWSI) given in eq. 2.

$$MCWSI = \frac{T_L - T_L^{WWB}}{T_L^{FWSB} - T_L^{WWB}} \qquad [eq. 2]$$

where T_L is leaf temperature measured at any time, T_L^{WWB} is leaf temperature for well-watered condition for a particular irrigation event and T_L^{FWSB} is leaf temperature for a fully water-stressed condition for the same irrigation event.

Jackson et al. (1981) plotted temperature difference of leaf to air (T_L – T_A) against vapor pressure deficit (VPD) showed that slope and intercept of well watered baseline (WWB) is temperature dependent. Therefore, different WWB was calculated for each tree after every irrigation event. The equation of the well-watered baseline (Jackson et al, 1981 eq.6) is shown below in eq. 3:

$$T_L - T_A = \frac{r_a R_n}{\rho c_p} \frac{\gamma}{\Delta + \gamma} - \frac{VPD}{\Delta + \gamma} \qquad [eq. 3]$$

where T_L and T_A are leaf and air temperature (°C), r_a is aerodynamic resistance (s/m), R_n is net radiation (W/m^2), ρ is density of air (kg/m^3), c_p is heat capacity of air (J/kg/°C), γ is psychrometric constant (Pa/°C), Δ is slope of the saturated vapor pressure-temperature relation [$e_s(T_L)$ – $e_s(T_A)$] / [T_L – T_A] in units of (Pa/°C), VPD is the vapor pressure deficit of air (Pa). According to eq. 3, WWB was calculated by regressing leaf temperature on its microclimatic parameters i.e. T_A, VPD, Δ, and photosynthetically active radiation (PAR). We found that T_A, VPD and Δ correlated with each other. Therefore, the first principal component (which explained more than 95% variabilty) calculated from these three variables were used in the regression analysis to avoid multicollinearity. Leaf temperature at well-waterd condition, T_L^{WWB} (eq.2) for a tree for any given irrigation event and for ith day after irrigation was calculated by:

$$T_L^{WWB} = (\beta_{01} + \beta_{11}x_{1i} + \beta_{21}x_{2i}) \qquad [eq. 4]$$

where, x_{1i}, x_{2i} are predictor variables for ith day (x_{1i} is PAR and x_{2i} is first principal component of T_a, VPD and Δ) β_{0i} is intercept, and β_{1i}, β_{2i} are regression cofficients from the well-watered day (i.e. i = 1) for particular irrigation event. For a stressed condition at any time, leaf temperature was assumed to be equal to air temperature at that time (as shaded leaves were chosen for measurements). Therefore, eq. 2 for MCWSI for ith day after irrigation event can be written as:

$$MCWSI^i = \frac{(\beta_{0i} + \beta_{1i}x_{1i} + \beta_{2i}x_{2i}) - (\beta_{01} + \beta_{11}x_{1i} + \beta_{21}x_{2i})}{(T_a^i) - (\beta_{01} + \beta_{11}x_{1i} + \beta_{21}x_{2i})} \qquad [eq. 5]$$

RESULTS AND DISCUSSION

Leaf monitor evaluation

Leaf monitors were successfully interfaced with the wireless nodes and were able to collect data continuously for 24 hours per day throughout the season. ekoView, the web page to see data over the internet, allowed monitoring of different variables by plotting temporal data. Figure 2 shows screen shots from eKoView of leaf monitor data. Figure 2(a) shows air temperature data measured by leaf monitors over a week in the orchard. Figure 2 (b) shows the typical pattern of temperature difference (T_A –T_L) data. As expected, temperature difference is close to zero at night times since there is negligible transpiration at night and leaf temperature is the same as air temperature. As the sun rises the leaf starts transpiring, which results in cooling of the leaf temperature with respect to air temperature; and temperature difference peaks after mid-day. Response of the temperature difference signal to irrigation can be seen from data corresponding to the first day after irrigation. The highest temperature difference for a given day decreases gradually for the days following the irrigation event which suggests that the leaf was transpiring less as a result of the tree getting water stressed. Continuous remote monitoring of data was very useful to detect any problem in the field such as malfunctioning sensor, communication breakdown, etc. It was found that wind speed was consistent in the dome. However, there were a few days at the end of the season (October) when wind speed was higher than other days and leaf temperature measurements were found to be sensitive to wind speed for these windy days. Light conditions (PAR) in the dome were also found to be consistent between different days for an irrigation event but variable between different trees. Also, low light levels on very cloudy days did have some effect on leaf temperature measurements. Overall four cloudy and two windy days were excluded from the data.

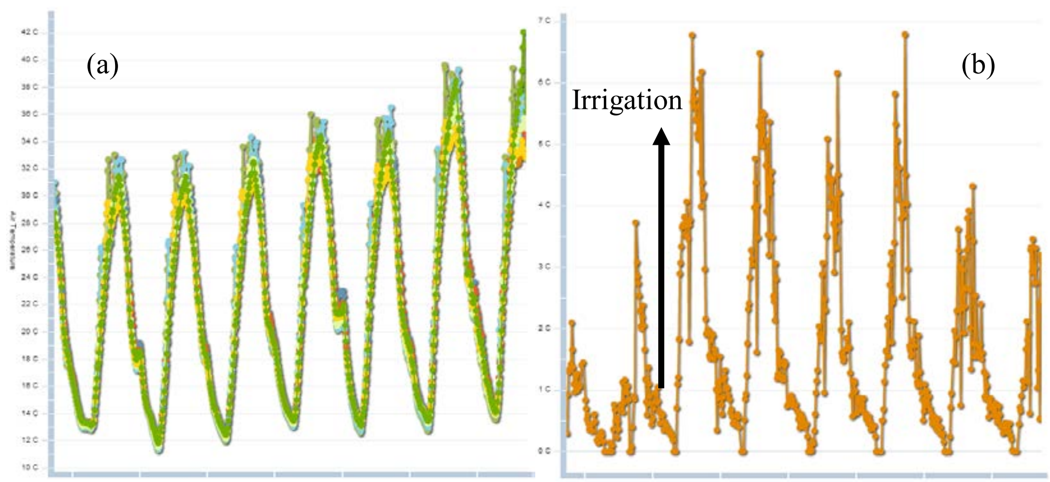


Figure 2: Screen shots of live leaf monitor (a) air temperature, ^{0}C data (b) Temperature difference ($T_a - T_L$), ^{0}C data from an almond leaf for eight consecutive days

Modified Crop Water Stress Index Evaluation

Well-watered baselines developed using eq. 4 yielded high coefficients of determination, in range of 0.95 to 0.99 for all trees for first day after irrigation. MCWSI values were calculated for mid-day (1 to 4 PM) using these baselines for different almond and walnut trees. Daily average MCWSI value was calculated for each tree using these instantaneous values. Figure 3 shows a typical pattern of MCWSI curve over consecutive days for an irrigation event of an almond and a walnut tree. Very low value of MCWSI was found for the first day and it further decreased for the second day showing that the tree was still recovering from water stress on the second day after irrigation. From the third day onwards CWSI increased rapidly at first, and then after a few days CWSI curve plateaued. This curve shows that transpiration from the leaf surface was decreasing for the first few days and then transpiration was very low as the tree became water-stressed.

Figure 4 shows daily MCWSI calculated for different almond and walnut trees throughout the season. Each curve represents plant response to a particular irrigation event. Breaks in the curve indicate irrigation events, and the first data point after break represents the first day after irrigation. The first or second day after irrigation was selected as a reference day by specially developed software, and this selected reference day had zero value of MCWSI. As seen in figures 4a, 4g, 4e, and 4f, there were a few irrigation events in which the MCWSI curve did not show the typical trend in figure 3. MCWSI values following irrigation remained close to zero or became negative, especially during the late season or after harvest in case of almonds (almond crop was harvested in mid-August). This might be important information for irrigation management, as almond and walnut growers are facing difficult challenges because of limited irrigation water availability. In some instances, there was an unexpected decrease in MCWSI values on the 4-5th day after irrigation, this situation usually occurred in trees which were over irrigated most of the time (i.e., first two curves in figure 4h). These issues will be further explored during the next season.

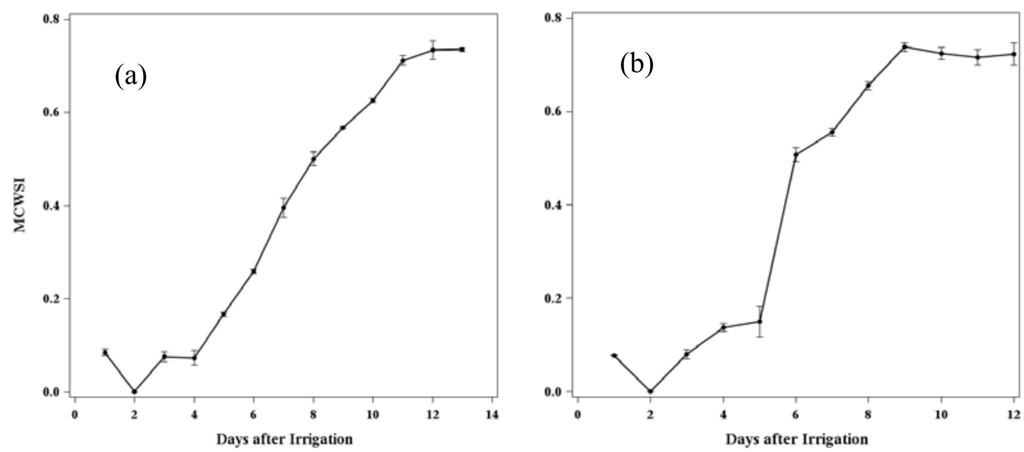
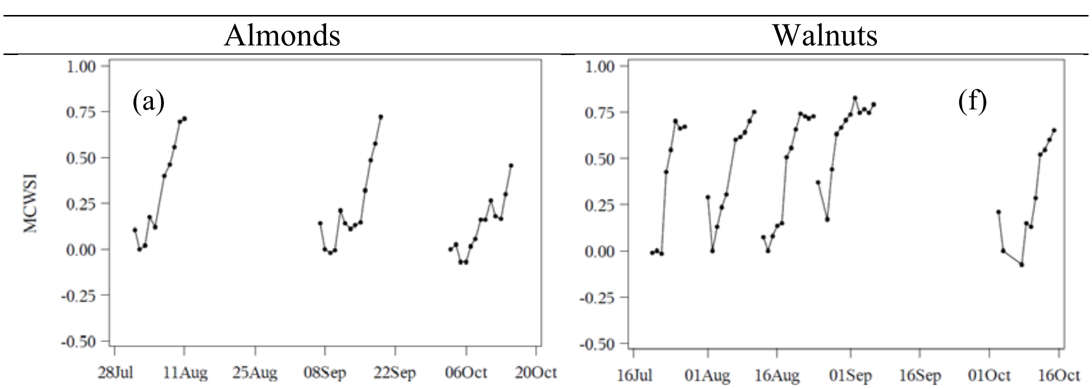


Figure 3: Typical pattern of MCWSI after an irrigation event for a (a) Almond (b) Walnut tree.



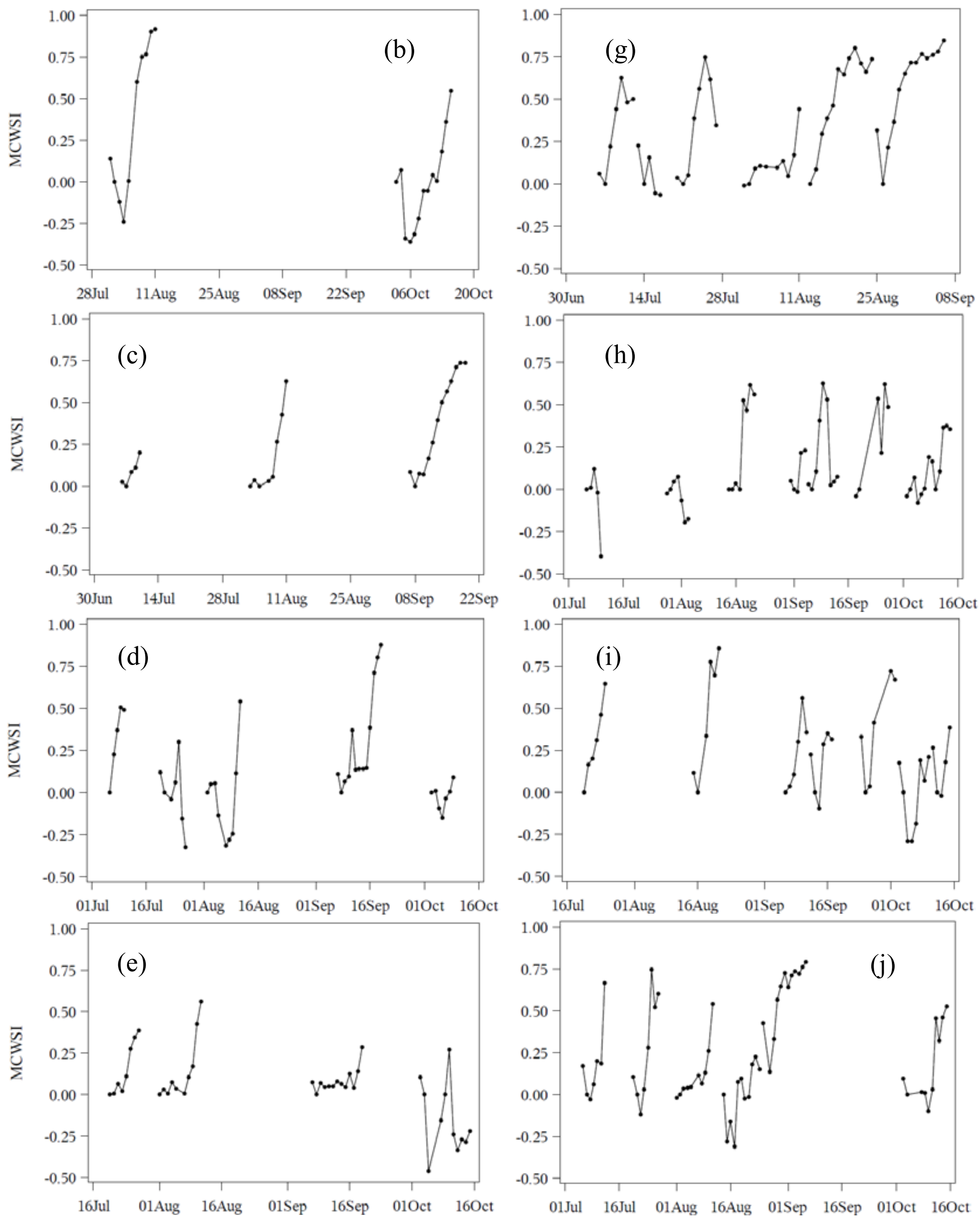


Figure4: MCWSI calculated from Leaf monitor data in almond (a-e) and walnut (f-j) trees. Each curve represents plant response following a particular irrigation event. Breaks in the curve precede irrigation event. Irrigation events of total number of days less than 5 were not considered in this analysis. (Almond trees were harvested during mid Aug to early Sep resulting in no data collection at that time).

Prediction of Plant water stress

MCWSI curve was also found to be correlated well with measured mid-day SWP. For this comparison, mid-day SWP was adjusted for weather conditions by calculating deficit SWP (DSWP). DSWP was calculated by subtracting measured

SWP from baseline SWP (BSWP) for almonds and walnut crop separately. BSWP represents SWP of a well-watered tree for given environment conditions. BSWP for almond (McCutchan and Shackel, 1992; Shackel et al., 1997), and walnut[1] crops are given by equations 6 and 7.

$$\text{Almonds: BSWP} = -0.120(\text{VPD}) - 0.410 \qquad \text{eq. 6}$$

$$\text{Walnuts: BSWP} = -0.064(\text{VPD}) - 0.278 \qquad \text{eq. 7}$$

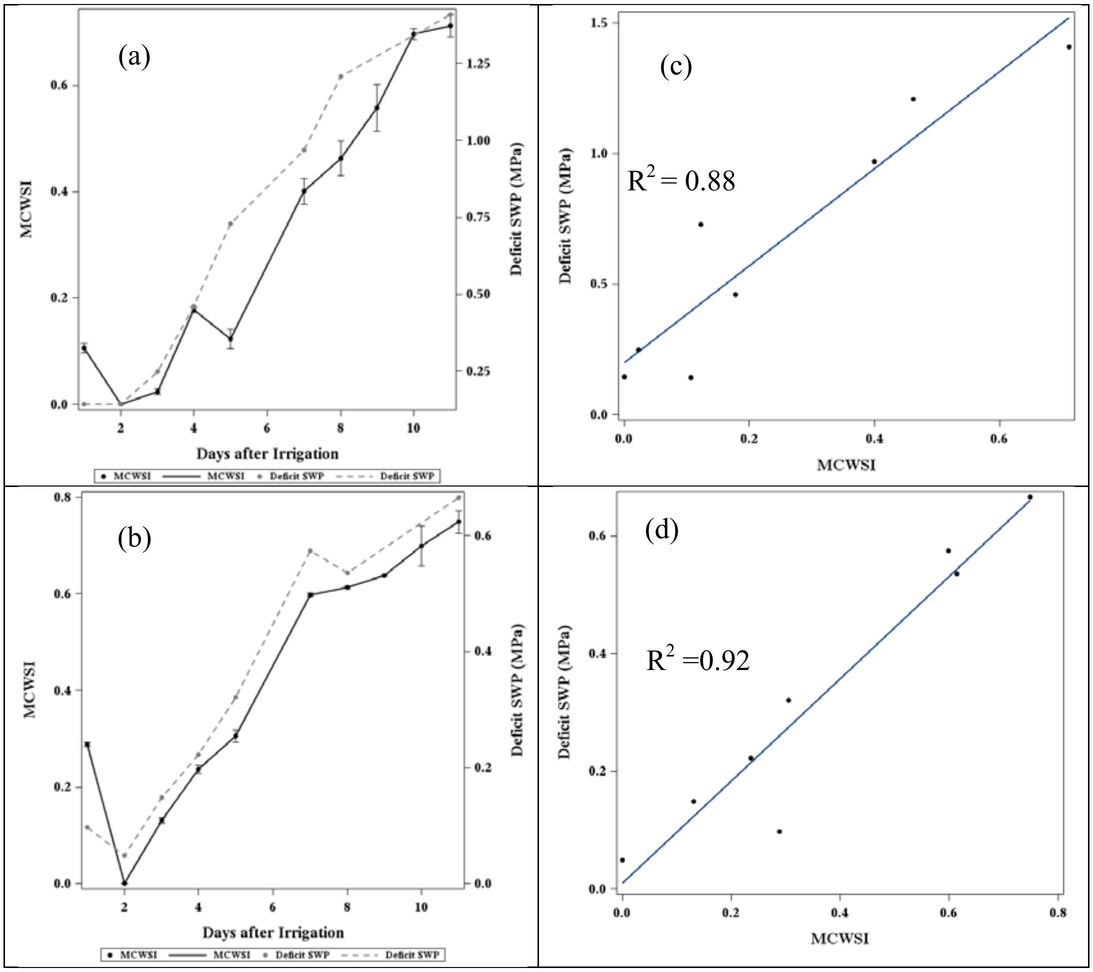


Figure 5: Daily MCWSI curve as compared with actual water stress level measured at mid-day following an irrigation event in (a) almonds, and (b) walnuts. Linear regression between daily MCWSI and measured Deficit SWP for (c) almonds, and (d) walnuts

Figure 5 shows both MCWSI and DSWP curves for an irrigation event for almond and walnut trees. Similar pattern of tree recovering for first two days after irrigation and then stress level increasing on following days can be seen in both curves. Measured DSWP was regressed on estimated MCWSI for these irrigation events, coefficient of determinations (R^2) of 0.88 and 0.92 were found for almond and walnut trees respectively (figure 5). Reasonably good results were found for most of the irrigation events, but R^2 was found to be close to 0.5 for two trees. Table 1 shows linear regression results for different irrigation events for other

[1] Baseline line equation for walnut crop is based on the unpublished work of the Dr. Kenneth Shackel, Professor, Department of Plant Sciences, UC Davis.

trees. Overall, MCWSI was able to predict DSWP with high R^2 for most of the trees. Relatively lower R^2 values in October could be because of relatively cold and humid environment present at that time and the onset of leaf senescing during that period. Some of these issues will be further explored during the next growing season. MCWSI calculated using the leaf monitor data is very useful to quantify plant water stress. Current results suggest that the leaf monitor that includes MCWSI algorithm can be a useful tool for irrigation scheduling. While these results are encouraging and demonstrate the potential use of a leaf monitor in implementing variable rate irrigation, future work is required to validate the ability of sensor system to predict plant water stress for different crops and weather conditions.

Table 1. Results obtained by linear regression of measured DSWP on calculated MCWSI for Almond and Walnut trees for irrigation events which had measured DSWP data for minimum 5 days.

crop	tree	month	RMSE	R^2	crop	tree	month	RMSE	R^2
Almond	1	Aug	0.11	0.73	Walnut	1	Aug	0.05	0.45
Almond	2	Aug	0.19	0.84	Walnut	2	Aug	0.1	0.59
Almond	3	Aug	0.19	0.5	Walnut	3	Aug	0.08	0.92
Almond	4	Aug	0.09	0.88	Walnut	4	Aug	0.13	0.55
Almond	4	Oct	0.11	0.69	Walnut	5	Oct	0.14	0.61

CONCLUSIONS

An inexpensive, easy to use sensing system called 'leaf monitor' was developed and evaluated to continuously measure leaf temperature and relevant microclimatic variables in the vicinity of a leaf for prediction of plant water status for tree crops. The system was tested in almond and walnut orchards for its ability to continuously monitor the leaf by logging leaf temperature, air temperature, relative humidity, wind speed and PAR (Photosynthetically Active Radiation). Data were accessed remotely over the web as leaf monitors were installed on trees as a part of wireless mesh network. Daily Modified Crop Water Stress Index (MCWSI) values were calculated by assigning the first day after irrigation as a reference day for incorporating any temporal variability in fully watered condition throughout the season. MCWSI values were found to be highly correlated with measured plant water stress. Measured DSWP was regressed on predicted MCWSI to obtain coefficient of determination values as high as 0.88 for almond and 0.92 for walnut trees. The leaf monitor has potential to be used as irrigation scheduling tool as it was able to provide daily stress index values that correlated well with traditional plant water stress measurements.

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