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A Continuous Leaf Monitoring System for Precision Irrigation Management in Orchard Crops

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Abstract: Studies have shown that measurement of plant water status (PWS) provides the key information necessary to implement efficient irrigation management scheme in orchard and vineyard crops. A pressure chamber is often used to measure PWS. However, this technique is labor intensive, tedious and time-consuming. To address these issues, we developed a sensor suite consisting of a thermal infrared (IR) sensor and relevant environmental parameters (ambient temperature, photosynthetically active radiation (PAR), wind speed and relative humidity) and tested it extensively in almond, walnut, and grape crops. The system was found to work well in all three crops. However, this sensor suite was quite bulky and we noticed temporal drifts in the calibration curve as the season progressed. To address these issues, we developed a continuous leaf monitoring system that included same sensors as the sensor suite. We have deployed 22 such leaf monitors in almond and walnut orchards in Nickels Soil Laboratory, Arbuckle, CA, USA and interfaced them to a wireless mesh network so that data could be uploaded to the internet through a gateway computer and accessed through the web. The system also included a controller capable of actuating latching solenoid valves to manage precision irrigation in the orchard. Field data collected from these experiments were used to calculate daily crop water stress index (CWSI). The results showed that this system has the potential to be used as irrigation management tool as it was able to provide daily CWSI values which followed similar pattern as the actual PWS values.

Key words: Leaf temperature, crop water stress index, cwsi, irrigation scheduling, continuous measurement, wireless mesh network, plant water status, almonds, walnuts, grapes

INTRODUCTION

Agriculture is an important component of California's economy accounting for approximately 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hand, California is leading in withdrawing irrigation water, consuming more than one-fourth of total irrigation water withdrawn in the nation (USGS, 2005). Recent draught 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. Irrigation scheduling techniques have been developed mostly based on soil moisture monitoring in the past. However, 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 that can be used to calculate Crop Water Stress Index (CWSI) to quantify plant water stress (Idso, 1981). 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). 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). 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; Dhillon et al., 2013). But these prediction equations were found to change during the season, which suggests a need to measure leaf temperature and other environmental parameters multiple times during the season that may not be practical. To overcome these issues, it is helpful to develop 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:

1. Develop a "leaf monitor" for continuous measurements of leaf temperature, and other relevant microclimatic variables.
2. Evaluate the performance of leaf-monitor for estimating plant water status as compared to conventional measurements in almond and walnut crops.

MATERIALS and METHOD

The Leaf Monitor is a sensor system to measure leaf temperature and relevant microclimatic parameters in the vicinity of a leaf on a continuous basis (figures 1 a and b). The sensor system consisted of an infra-red thermometer (IRT) (Melexis MLX90614ESF-BCF-000-TU) to measure leaf temperature. This sensor had 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 5V 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 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 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 customized PC 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 selected to make continuous leaf temperature measurements had to be fixed in front of the infrared sensor to make sure that the sensor was always looking at the leaf surface. Leaf holder, basically consisted of mesh of nylon wire around two metal rings. Leaf was held between these two rings and position of rings could be adjusted according to leaf orientation. We found that at times surface of 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 is installed to suppress 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 leaf, leaf temperature is expected to be less influenced by environmental conditions.

Twenty two leaf monitors were installed on shaded leaves of almond and walnut trees (figures 1a and b) at Nickel's SoilLab, Arbuckle, CA. They were interfaced using a RS485 module to nodes of an existing wireless mesh network (Coates et al., 2012) at the field site for precision irrigation control using latching solenoid valves. These nodes transmit the sensor data to a gateway computer, which in turn uploads the data to the internet so that the data can be viewed from anywhere using a web browser. 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 which ensured that the leaf water potential of that leaf was in equilibrium with SWP.

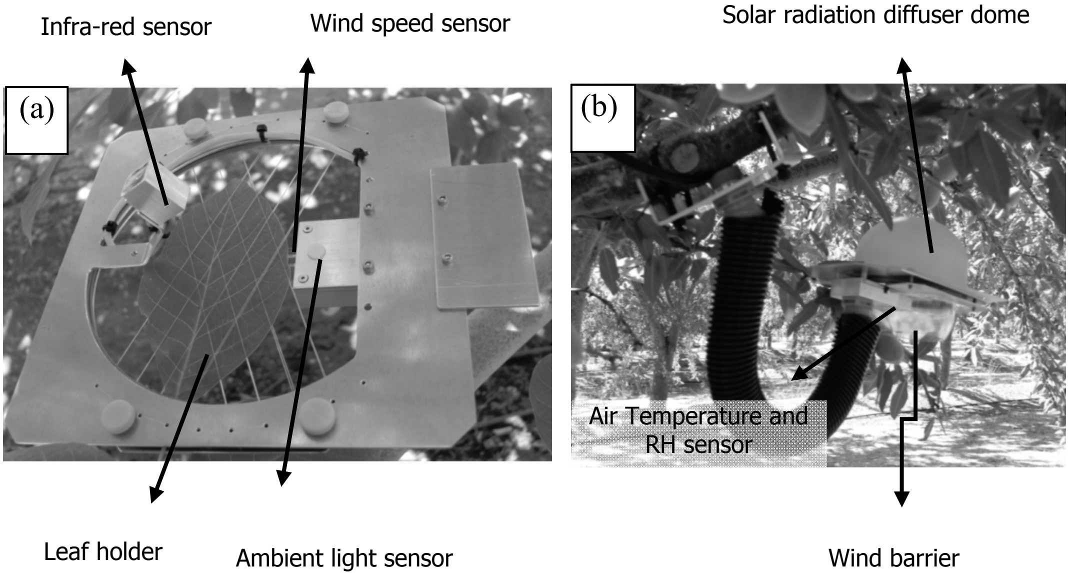

Figure 1. Leaf monitor installed on (a) walnut tree (picture taken before installing dome) and, (b) almond tree for field testing

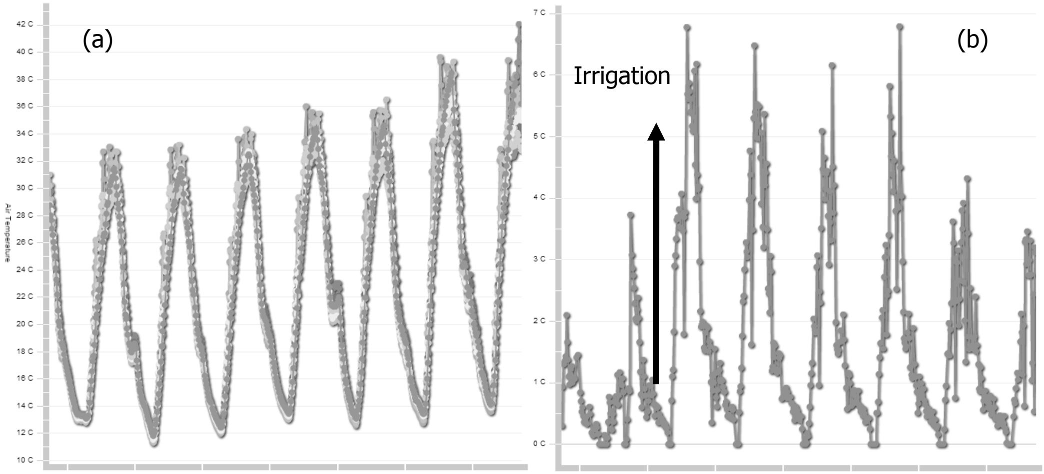

Figure 2. Screen shots of live leaf monitor (a) air temperature, °C data (b) Temperature difference (Ta – TL), °C data from an almond leaf for eight consecutive days

RESULTS and DISCUSSION

Figure 2 shows screen shots of leaf monitor data obtained from a laboratory computer. 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 ($T_{air} - T_{leaf}$) data. As expected temperature difference is close to zero at night times since there is negligible transpiration at night and leaf temperature is 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 temperature difference signal to irrigation can be seen from data corresponding to first day after irrigation. The magnitude of highest temperature difference for a given day decreases gradually for the days following the irrigation event which suggests that leaf is transpiring less as a result of the tree getting water stressed. Well watered baseline for each zone (spatial) and irrigation event (temporal) were developed using leaf monitor data obtained on the first day following an irrigation event. Using these baseline curves, spatially and temporally variable CWSI values termed modified CWSI (MCWSI) values were calculated. Figure 3 shows a typical pattern of MCWSI curve over consecutive days following 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 second day showing that 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 had a plateau. This curve shows that transpiration from leaf surface was decreasing for first few days and then transpiration was very low as tree got water-stressed. MCWSI values were compared with respective measured mid-day SWP. For this comparison, mid-day SWP was adjusted for weather conditions by calculating deficit SWP (DSWP). Figures 4a and b show MCWSI curves for an irrigation event for almond and walnut trees, respectively. Measured DSWP values were regressed against estimated MCWSI values for these irrigation events using a simple linear regression technique. Coefficient of determination values of 0.88 and 0.92 were found for almond and walnut trees respectively (figures 4c and d).

These 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 leaf monitor for implementing variable rate irrigation, additional work is required to validate the ability of sensor system to predict plant water stress for different crops and climatic conditions.

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. 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 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 well correlated with measured plant water stress. Measured DSWP values were found to be correlated with predicted MCWSI values with coefficient of determination values of 0.88 for almond and 0.92 for walnut trees. Leaf monitor has the potential to be used as an irrigation scheduling tool as it was able to provide daily stress index values that resembled actual plant water stress measurements.

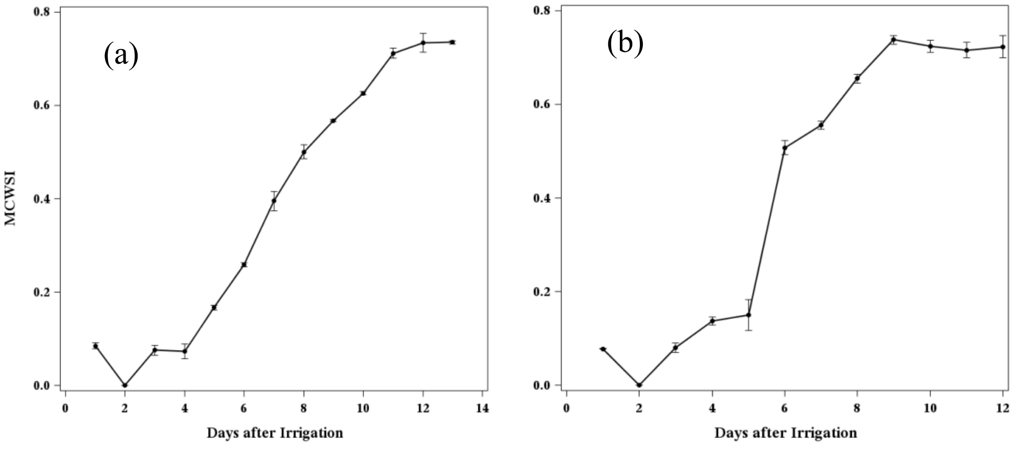

Figure 3. Typical pattern of MCWSI after an irrigation event for a (a) Almond (b) Walnut tree.

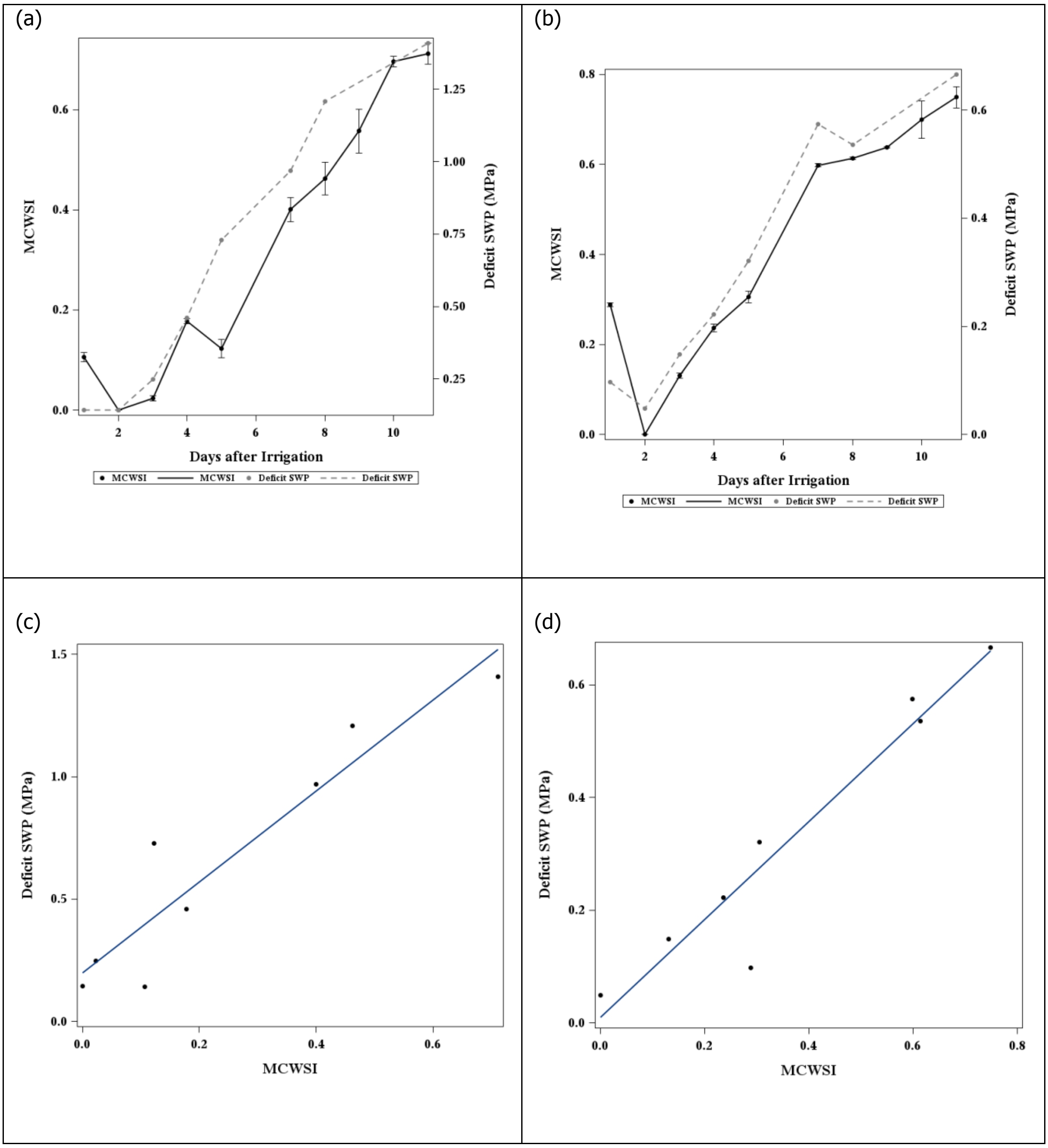

Figure 4. Daily MCWSI curve as compared with actual water stress level measured at mid-day following an irrigation event in (a) almonds, and (b) walnuts. Linear regression between daily MCWSI and measured Deficit SWP for (c) almonds, and (d) walnuts.

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