DEVELOPMENT OF A SENSOR SUITE TO DETERMINE PLANT WATER POTENTIAL

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ABSTRACT

The goal of this research was to develop a mobile sensor suite to determine plant water status in almonds and walnuts. The sensor suite consisted of an infrared thermometer to measure leaf temperature and additional sensors to measure relevant ambient conditions such as light intensity, air temperature, air humidity, and wind speed. In the Summer of 2009, the system was used to study the relationship between leaf temperature, plant water status, and relevant microclimatic information in an almond and a walnut orchard. A pressure chamber was used to measure stem water potential to represent the plant water status. Empirical prediction equations for temperature difference between leaf and air ($T_L - T_a$) as functions of stem water potential, light intensity, air vapor pressure deficit, and wind speed were developed and validated for both crops. We found that wind speed was not significant for both crops in our experiments. Air vapor pressure deficit was significant only in almonds. The R^2 values for the prediction equations were 0.71 and 0.70 for almonds and walnuts, respectively. These models were able to predict ($T_L - T_a$) for the respective validation sets quite well. The R^2 value for the validation sets was 0.76 for both crops. To improve the predictability, data measured from multiple leaves on the same tree under similar lighting conditions were averaged. The R^2 values improved to 0.83 and 0.84 for almonds and walnuts, respectively when these average values were used in developing prediction equations. These results demonstrate the feasibility that the sensor suite can be used to determine plant water status.

Keywords: plant water potential, plant water status, leaf temperature, infrared thermometer

INTRODUCTION

For most crops, quality and quantity of production are directly related to crop water use. Inadequate water application often decreases yield and quality of the product. Over-application would lead to water wastage. The key is to develop irrigation strategies for better water use efficiency without impacting quality or yield of the produce. To improve irrigation efficiency, plant water status must be monitored (Shackel et al., 1997).

Pressure chamber (Scholander et al., 1965) has been used widely to measure leaf water potential for water deficit determination and irrigation scheduling for many crops (Garnier and Berger, 1985; Shackel et al., 1997; Goncalves and Santos, 2000; Naor, 2000; Choné et al., 2001; Lampinen et al., 2001; Chauvin et al., 2006; Doltra et al., 2007). Leaf conductance is sensitive to plant water status and physiological processes (Gates, 1980; Jones, 1992) which is useful for irrigation scheduling (Bugbee et al., 1998; Jones, 1999; Leinonen et al., 2006). Torrecillas et al.(1988) and Shackel (2007) found a good correlation between leaf conductance and stem water potential in almonds.

However, these conventional methods that use pressure bomb or leaf porometer are tedious and time consuming, and frequently result in an inadequate amount of sampling (Cohen et al., 2005; Leinonen et al., 2006). It is not feasible to use them in commercial applications (Jones, 2004). To address these concerns, techniques based on measuring canopy temperature have been developed. When plant is under stress due to lack of water, it tends to close the stomata and lower stomatal conductance to decrease transpiration. This reduced stomatal conductance or transpiration leads to an increase in leaf temperature. However, an energy balance of the leaf shows that this change in leaf temperature also depends on ambient conditions (i.e., relative humidity, wind speed, and ambient temperature) and radiation incident on the canopy surface. Although these parameters influence canopy temperature, they can be easily measured in real-time using commercially available sensors. Sensing canopy temperature using infrared thermometers or thermal cameras has shown good potential to estimate plant water status for irrigation scheduling in many crops (González-Dugo et al., 2006; Payero and Irmak, 2006; Moller et al., 2007; Testi et al., 2008). Thermal imaging technique can be scaled up to large areas of crop (Jones, 2004) but involves image processing techniques and can be expensive. Simple infrared thermometers with proper acquisition techniques could be used as rapid and noncontact sensing devices to evaluate plant water status.

The aim of this study is to develop a sensor suite for field measurement of leaf temperature and relevant microclimate information to determine plant water status in almonds and walnuts. Field experiments were conducted to explore the feasibility of using such a sensor suite to determine plant water status.

THERMAL SENSING FOR PLANT WATER STATUS

Responses of a plant leaf to plant water status and environmental parameters can be analytically modeled using an energy balance equation, which can be expressed in terms of energy flux density as shown in equations 1 to 3 (Jackson et al., 1988). Net radiation flux is the net flux of all radiation across the leaf surface. Sensible heat flux is the rate of heat loss across the leaf surface to the surrounding mostly by convection. Latent energy flux is rate of heat loss across the leaf surface by evaporation. For a leaf, energy generated form metabolic processes and energy stored in or generated by plant organism can be neglected (Jones, 1992).

$$R_n = H + \lambda E \tag{1}$$

$$H = \frac{\rho c_p (T_L - T_a)}{r_a} \tag{2}$$

$$\lambda E = \frac{\rho c_p (e_L^* - e_a)}{\gamma (r_L + r_a)} \tag{3}$$

where R_n = net radiation flux density [W m^{-2}]
H = sensible heat flux density [W m^{-2}]
λE = latent energy flux density [W m^{-2}]
$T_L - T_a$ = difference between leaf temperature (T_L) and air temperature (T_a) [°C]
r_L = leaf resistance to water loss [s m^{-1}]
r_a = boundary layer resistance [s m^{-1}]
ρ = density of air [kg m^{-3}]
c_p = specific heat capacity of air [J kg^{-1} $°C^{-1}$]
γ = psychometric constant [Pa $°C^{-1}$].

Substitution of equations 2 and 3 in to equation 1 yields

$$T_L - T_a = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma (r_L + r_a)}{\gamma (r_L + r_a) + s r_a} - \frac{r_a VPD}{\gamma (r_L + r_a) + s r_a} \tag{4}$$

where s = slope of the saturated vapor pressure-temperature relation [kPa $°C^{-1}$]
= $(e_L^* - e_a^*)/(T_L - T_a)$ assumed to be a constant over the range T_a to T_L
VPD = air vapor pressure deficit [kPa] = $e_a^* - e_a$
e_L^* = saturated vapor pressure at leaf temperature [kPa]
e_a^* = saturated vapor pressure at air temperature [kPa]
e_a = vapor pressure at air temperature [kPa].

Boundary layer resistance (r_a) depends mainly on the shape and size of the leaf, and wind speed. Leaves of many plants can be approximated as flat plates (Gates, 1980). For laminar flow over flat plates, boundary layer resistance can be approximated by $r_a = 151.06\ (d/u)^{0.5}$ where d and u are characteristic dimension [m] and wind velocity [m s^{-1}], respectively (Jones, 1992). Leaf resistance (r_L) is the inverse of the leaf conductance. In this study, stem water potential measured by a pressure chamber was used instead of leaf conductance as it has been found to have a good relationship with plant water status in almonds (Torrecillas et al., 1988; Shackel, 2007).

An infrared thermometer (IRT) can be used to measure temperature of leaf or canopy by detecting infrared energy emitted. This emitted radiant energy flux density, E [W m^{-2}], is converted into temperature, T [K], by the Stefan-Boltzman law, $E = \varepsilon\sigma T^4$, where ε is the emissivity of the object, and σ is the Stefan-Boltzman constant (5.68×10^{-8} J m^{-2} s^{-1} K^{-4}) (Bugbee et al., 1998). Emissivity is defined as the radiation efficiency of a surface as compared to an ideal black body emitter. Typically, plant leaves have emissivity between 0.94 to 0.99 and slightly higher for a whole canopy due to reflectance within the canopy (Jones, 1992).

MATERIALS AND METHOD

To study the relationship between leaf temperature and plant water status, we have developed a sensor suite to measure leaf temperature and relevant microclimate information. The sensor suite consists of an infrared thermometer (4000.4ZL, Everest Interscience, Tucson, AZ), a quantum sensor (LI-190, LICOR inc., Lincoln, NE), an anemometer (VelociCalc 8360, TSI Inc., Shoreview, MN) and air temperature and relative humidity probe (HMP35C, Visalia Inc., Woburn, MA) interfaced to a CR3000 datalogger (Campbell Scientific Inc., Logan, UT).

The sensor suite was used in an almond orchard (19 years old Nonpareil variety) and a walnut orchard (7 years old Howard variety) located at Arbuckle, California. Measurements were taken at two different times for both almonds and walnuts. Table 1 lists the range of water potentials and ambient conditions during field measurements.

Table 1. Experimental dates and range of parameters.

Crop	Date	Trees	Range			
			stem water potential	air temperature	VPD	wind speed
			MPa	°C	kPa	m s^{-1}
Almond	7/21/09	26	-4.60 to -0.72	29.2 to 34.3	2.3 to 3.6	0.1 to 1.4
Almond	8/3/09	36	-3.96 to -0.93	24.9 to 29.4	1.6 to 2.6	0.1 to 1.8
Walnut	7/29/10	13	-0.94 to -0.31	31.0 to 32.5	2.2 to 2.8	n/a
Walnut	8/8/09	15	-1.35 to -0.40	29.3 to 32.9	2.2 to 3.5	0.0 to 1.1

For each tree, temperatures of both sunlit and shaded leaves were measured using the infrared thermometer. Air temperature, relative humidity, and wind speed were measured in the vicinity of the target leaf at the time of leaf temperature measurement. Light intensity was measured immediately after each temperature measurement using a quantum sensor in the normal direction to the leaf surface. In addition, to minimize transient effects, temperature measurements were taken only when the sky was not overcast and wind was still or calm.

A pressure chamber (3005-Series, Soilmoisture Equipment Corp., Santa Barbara, CA) was used to measure stem water potential (SWP) from shaded interior leaves that were wrapped with foil-covered plastic bags at least 15 minutes before the measurements to prevent the leaves from transpiring so that their water potential can equilibrate with their respective stems. The stem water potential measurement was taken within 10 minutes prior to sensor suite measurements.

RESULTS AND DISCUSSIONS

Experimental data for each crop were randomly split into calibration and validation sets. The calibration set consisted of approximately 60% data and the validation set consisted of remaining 40% data. Using a multiple linear regression technique that utilized stepwise model selection procedure, empirical prediction equations for $(T_L - T_a)$ were developed for both crops and are presented in table 2 (equation 5 for almonds and equation 6 for walnuts). Independent parameters were stem water potential, light interception, wind speed, and air vapor pressure deficit. For almonds, all parameters except wind speed were significant. The lack of significance of wind speed might be due to calm wind conditions that prevailed during the experiments. The R^2 value for the calibration data was 0.71 (equation 5).

For walnuts, wind speed data were not available for 7/29/09 tests. However, analysis of walnut data obtained on 8/8/09 indicated that wind speed was not significant. This outcome might be due to calm wind conditions prevalent during the experiments on that day (table 1). Moreover, based on the wind data from a nearby CIMIS (California Irrigation Management Information System, http://wwwcimis.water.ca.gov) station at Esparto, CA, the prevailing wind conditions for both 7/29/09 and 8/8/09 during period of experiment (noon to 3:00 PM) were found to be similar. Therefore, our analysis for walnuts will exclude the wind speed parameter. The R^2 value for the calibration set was 0.70 (equation 6). Note that the vapor pressure deficit was not significant for walnuts.

Table 2. Empirical prediction models developed by the calibration data sets and the R^2 values corresponding to both calibration and validation data sets.

Crop	Empirical prediction model†	R^2 value		
		calibration set	calibration set	
Almond	$Y = 2.83648 - 0.00164\ X_1 \cdot X_2 - 1.23827\ X_3$	0.714	0.758	(5)
Walnut	$Y = -1.74557 - 0.00693\ X_1 \cdot X_2$	0.699	0.759	(6)

† Y = $(T_L - T_a)$ [°C]
X_1 = stem water potential [MPa]
X_2 = photosynthetically active radiation [μmol s^{-1} m-^{2}]
X_3 = air vapor pressure deficit [kPa]
X_4 = wind speed [m s^{-1}]

Figures 1 and 2 show the comparison between predicted and measured $(T_L - T_a)$ for the calibration set (figures 1a for almonds and 2a for walnuts) and the validation sets (figures 1b for almonds and 2b for walnuts). The measured versus predicted data for the calibration as well prediction sets shown in these figures not only resulted in high R^2 values, the slopes are nearly unity and intercepts are almost zero indicating models with good predictive abilities. When the calibration equations were used on the prediction data sets, high R^2 value of 0.76 resulted for both crops. These results are very promising and indicate that the sensor suite could be used to determine plant water status.

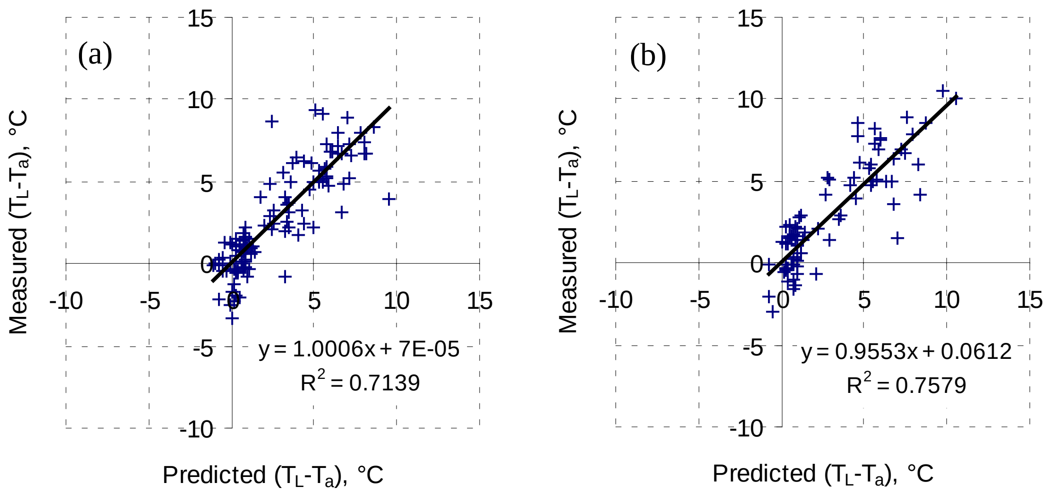

Figure 1. Plots of predicted vs. measured ($T_L - T_a$) for almonds using both datasets obtained on 7/21/09 and 8/3/09. Sixty percent of all data were sprit into (a) calibration set to develop a prediction model (equation 5) and the rest of data were used as (b) validation set to validate the model.

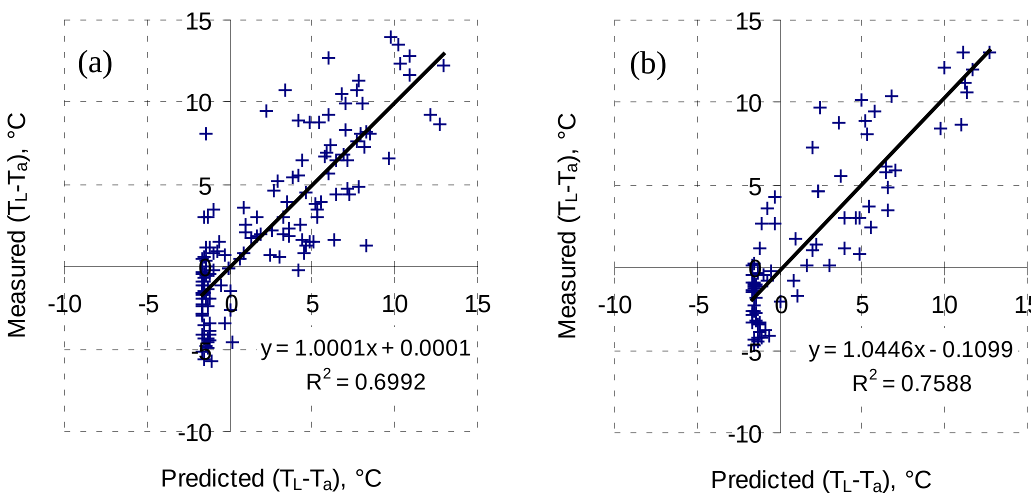

Figure 2. Plots of predicted vs. measured ($T_L - T_a$) for walnuts using both datasets obtained on 7/29/09 and 8/8/09. Sixty percent of all data were sprit into (a) calibration set to develop a prediction model (equation 6) and the rest of data were used as (b) validation set to validate the model.

Since stem water potential represents overall plant water status, it may be better to measure temperature and ambient conditions in the vicinity of multiple leaves on a tree and use the average values for leaves in similar lighting conditions to determine plant water status. Fortunately, almond data obtained on

8/3/09 and walnut data on 7/29/09 consisted of 2 to 3 set of measurements per tree under similar lighting conditions (i.e., multiple sunlit and multiple shaded leaves were measured). Use of average values corresponding to leaves under similar conditions, resulted in improvement in R^2 values from 0.76 to 0.83 for almonds (figures 3a and 3b) and from 0.80 to 0.84 for walnuts (figures 4a and 4b). This is very encouraging and we plan to further explore this possibility during the 2010 growing season.

Table 3. Empirical prediction models for the data sets that have multiple data under similar lighting conditions on the same tree. Models were developed using individual measurements and the average data.

Crop	Date	Data used	Empirical prediction model†	R^2 value	
Almond	8/3/09	Individual	$Y = 0.31720 - 0.00192\ X_1 \cdot X_2 + 0.00023\ X_1 \cdot X_2 \cdot X_3 \cdot X_4$	0.7556	(7)
		Average	$Y = 0.17118 - 0.00207\ X_1 \cdot X_2 + 0.00031\ X_1 \cdot X_2 \cdot X_3 \cdot X_4$	0.8332	(8)
Walnut	7/29/09	Individual	$Y = -1.22772 - 0.02416\ X_1 \cdot X_2 + 0.00662\ X_1 \cdot X_2 \cdot X_3$	0.7962	(9)
		Average	$Y = -1.10269 - 0.00718\ X_1 \cdot X_2$	0.8361	(10)

† Y = $(T_L - T_a)$ [°C]
X_1 = stem water potential [MPa]
X_2 = photosynthetically active radiation [μmol s^{-1} m-^{2}]
X_3 = air vapor pressure deficit [kPa]
X_4 = wind speed [m s^{-1}]

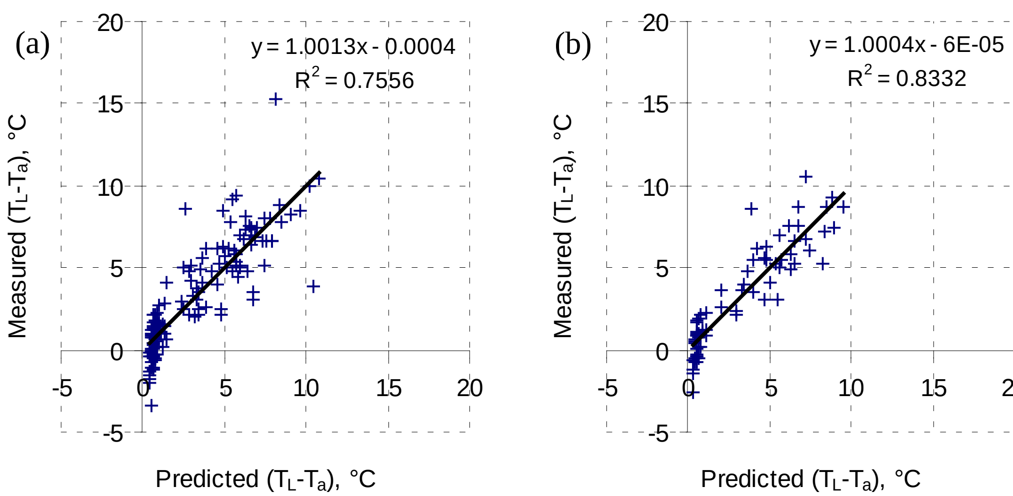

Figure 3. Plots of predicted vs. measured leaf–air temperature ($T_L - T_a$) for almonds to show effect of using average data. The model was developed using 8/3/09 dataset that represents (a) individual measurements, and (b) averaged data from the same lighting conditions and same tree.

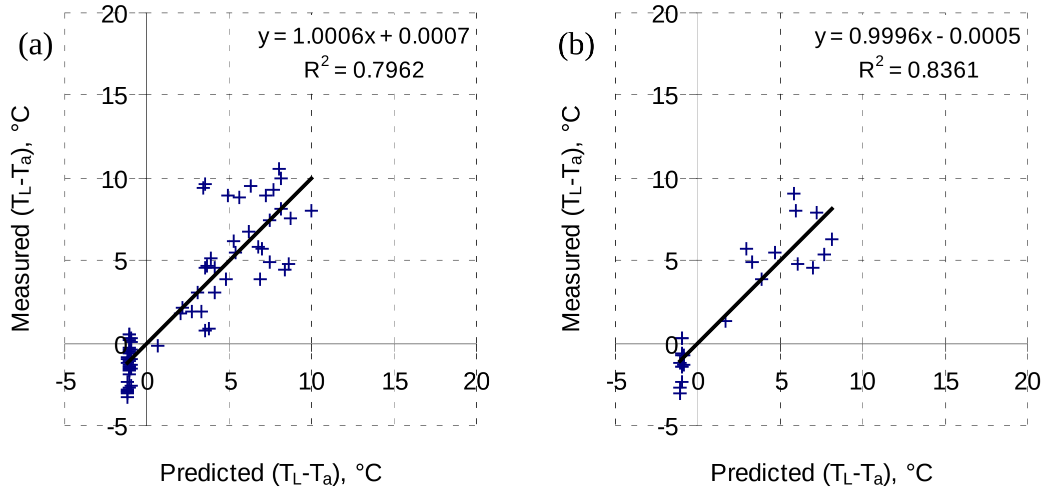

Figure 4. Plots of predicted vs. measured leaf−air temperature ($T_L - T_a$) for walnuts to show effect of using average data. The model was developed using 7/29/09 dataset that represents (a) individual measurements, and (b) averaged data from the same lighting conditions and same tree.

It should be noted that our ultimate interest is to predict plant water status (i.e., either stem water potential or leaf conductance) using the data obtained from various sensors included in the sensor suite. This requires the prediction of stem water potential or leaf conductance using temperature differential between leaf and its surrounding and other environmental data. Often indices such as crop water stress index (CWSI) (Idso et al., 1981; Jackson et al., 1981; Jackson et al., 1988) are used to indicate plant water status. We are currently exploring these interesting possibilities.

CONCLUSION

A portable sensor suite consisting of an infrared thermometer and sensors for relevant ambient conditions was developed and used to measure leaf temperature, light intensity, air temperature, air humidity, and wind speed in almonds and walnuts with different levels of stem water potential. Empirical models were developed for both almonds and walnuts for the temperature differential between the leaf and surrounding air as a function of stem water potential, light intensity, vapor pressure deficit, and wind speed. These empirical relationships resulted in high R^2 values in the range of 0.70 and 0.71 for almonds and walnuts, respectively. In addition, we found that use of average data for multiple leaves under similar lighting conditions (sunlit or shaded) results in an improvement in R^2 value for both almonds and walnuts indicating that it is better to use average values of temperatures and associated ambient conditions of similarly lit leaves to improve the model.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Prof. Ken Shackel, Plant Sciences Department, University of California at Davis for his assistance in providing stem water potential data. Moreover, we sincerely appreciate the financial support received from Almond Board of California and California Walnut Board to conduct these research activities.

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