Development and Testing of a Mobile Platform for Measuring Canopy Light Interception and Water Stress in Almond

Project No.: 13-HORT13-Lampinen

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Objectives:

Objective 1) The first component of this project involves using the mobile platform lightbar to measure light interception and corresponding yield in almond orchards throughout the almond growing area of California. The goal of this aspect of the work is to help establish the upper limit to the light interception/yield relationship for almond (shown in **Figure 1**) as well as to use these data to investigate the relationship between productivity and productivity per unit light intercepted.

Objective 2) The second component of the project involves continuing work on new methods of measuring water stress in almond.

Objective 3) An application to allow farm advisors and growers to estimate canopy light interception using an iPhone is being developed and tested.

Interpretive Summary:

A mobile platform for measuring midday canopy light interception and a sensor suite for measuring leaf/canopy temperature as a means of assessing plant water status has been developed.

Mobile platform - Data collected by the authors over the past several years has provided a rough upper limit to productivity in almond based on the percentage of the available midday canopy photosynthetically active radiation (PAR) that is intercepted and the age of the trees. However, most of the data that was collected previously had limitations. The methods of measuring percent PAR interception using a handheld lightbar (Decagon Devices, Pullman, WA 99163) were relatively slow and labor intensive. For this reason, much of the lightbar data that was used to develop the relationship was based on sampling of relatively small samples of trees. Often the area for the yield and PAR interception data did not match (i.e. PAR data from 5 trees and yield data from either one tree or from an entire row). We have outfitted a Kawasaki Mule with a light bar that is able to measure light across an entire row (up to 32 feet wide). The data can be stored on a datalogger at intervals of less than 1 foot down the row at a travel speed of about 4.5 mph giving us a much better spatial resolution in much less time than was possible in the past.

The mobile platform was used extensively for mapping midday canopy light interception in almond orchards. The 2013 season was the fifth year that data was collected with the mobile platform. Data collected with the mobile platform suggests that there are a number of potential uses for this technology. The first is for providing a baseline for assessing how an orchard is performing relative to other orchards of similar age and variety. Another is for separating out the effects of rate of canopy growth from productivity per unit canopy light intercepted in different clones or varieties. A third potential use is for assessing the efficacy of different fumigants by again separating out the effects of canopy size from productivity per unit light intercepted. A fourth use is for evaluating the impacts of different pruning regimes on canopy growth, light interception and productivity per unit light intercepted. This technology also allows the elimination of canopy size differences from any type of trial.

Sensor suite - In 2012, the sensor suite was upgraded to a more compact design. The device uses an IR spot sensor to measure leaf temperature while accounting for windspeed, leaf orientation, and incident PAR to provide a potential means of detecting plant water status. Results from the 2012 and 2013 seasons continued to show promise for this technique to predict stem water potential. Data again showed that shaded leaves give better results than sunlit leaves.

Leaf monitor - The leaf monitor for continuously measuring leaf to air temperature difference in the lower canopy was refined and tested. The leaf monitor is able to track almond tree water stress over an irrigation cycle with the results comparing well with midday stem water potential measurements using the plant pressure chamber suggesting the device could be used for continuous monitoring of plant water status.

Development of the iPhone app is ongoing with release to farm advisors and growers expected in the spring and summer of 2015.

Materials and Methods:

<u>Objective 1</u> - Refine light interception/yield relationship in almond. Twenty two almond orchard sites of varying ages and varieties from throughout the almond growing area of California were selected for measurements in 2013 (**Table 1**). An emphasis was placed

on orchards with Nonpareil but other varieties were also included. Light bar measurements were done in 10-20 rows (depending on orchard size and variability) in representative areas of the orchard during June to August. In addition, measurements were done in various research plots around the state as described below. A portable weather station with temperature, relative humidity and photosynthetically active radiation sensors was set up outside of each orchard to provide reference data (on a one minute basis) during the period measurements with the light bar were being taken. The photosynthetically active radiation data from this station was used to calibrate the sensors on the Mule lightbar throughout the measurement period. The data rows were then flagged and at harvest time, rough field weights were taken from the Nonpareil or other primary variety in the orchards. Subsamples from each variety were taken and dried and shelled to estimate kernel yield. In some cases measurements were done in orchards that are being used for other almond trials including sites from the USDA-ARS Area Wide Methyl Bromide Alternatives trials, as well as projects funded under a federal

Table 1. Almond orchards sites mapped with Mule lightbar during 2013 season

Site #	County	Trial	Date Mapped	Site #	County	Trial	Date Mapped
1	Kern	SCRI-Belridge	6/28/2013	12	Kern	Paramount hedging trial	7/20/2013
2	Kern	Spur Dynamics	6/29/2013	13	Merced	Doll WPF	7/27/2013
3	Kern	Paramount 3541 fumigation trial (fumigated replicates)	6/30/2013	14	Stanislaus	Duncan almond pruning, spacing and rootstock	7/28/2013
4	Colusa	Nickels organic almond	7/3/2013	15	Madera	Agriland irrigation trial	7/29/2013
5	Colusa	Nickels almond rootstock	7/4/2013	16	Madera	Agriland fumigation trial	7/29/2013
6	Colusa	Nickels almond pruning/training trial	7/4/2013	17	Madera	Madera Growers South	7/30/2013
7	Colusa	Nickels precision irrigation	7/5/2013	18	Madera	Paramount New Columbia main fumigation trial	7/31/2013
8	Tehama	ETPF Fulton	7/11/2013	19	Madera	Paramount New Columbia fumigation/irrigation trial	7/31/2013
9		Paramount 3541 fumigation trial (non-fumigated replicates)	7/14/2013	20	Merced	Browne Littlejohn almond	8/7/2013
10	Kern	Kern WPF	7/16/2013	21	Merced	Browne Frago trial	8/8/2013
11	Kern	McFarland Variety trial	7/17/2013	22	Merced	Bandoni	8/16/2013

SCRI grant focused on fertilization efficiencies. Other orchards were mapped from rootstock as well as pruning and training trials. Using orchards from other studies allows us to utilize the data for multiple purposes.

Objective 2 - A mobile sensor suite (**Figure 3**) was developed and evaluated to predict plant water status by measuring the leaf temperature of nut trees and grapevines. It consists of an infrared thermometer to measure leaf temperature as well as sensors to measure air temperature, relative humidity, wind speed, and photosynthetically active radiation (PAR) in the vicinity of the leaf. In 2012, the sensor suite was redesigned to a much more compact format.

In 2013, a leaf monitor for measuring shaded leaf temperature on a continuous basis was refined and tested in the field. UC Davis has applied for a patent for this device. Continuous leaf monitors were installed on shaded almond leaves (**Figure 6**) at Nickels Soil Lab, Arbuckle, CA. Leaf monitors were integrated into an existing eKo wireless sensor network at the field site used for precision irrigation control. Leaf monitor data was collected every 15 minutes from July through early October. These data were stored in a database on the field computer at the base station and were available to access in real-time from the web. Plant water status was also measured to ground-truth data. Midday stem water potential for each tree on which a leaf monitor was installed was measured using the pressure chamber after enclosing a shaded leaf in a mylar bag for at least 20-30 minutes.

Results and Discussion:

Objective 1 - Data collected with the Mule lightbar in from 2009-2013 are shown in **Figure 1**. Although many orchards produced yields well above the sustainable upper limit line in 2009 and 2011, in 2010 and 2012 they were well below the line, and the overall regression for all years is below the line. Since individual spurs alternate bear, yields can be shifted from a low yield year to the following year. If a low percentage of spurs bear in one year (for example due to poor bloom time weather), the next year a larger percentage of spurs will have a higher percentage chance of bearing.

The data collected with the mobile platform lightbar has many potential uses. One potential use is to help interpret data from pruning and spacing trials. **Figure 2** shows the 2013 midday canopy light interception versus the cumulative yield (years 6-14) for a pruning and spacing trial in Stanislaus County. **Figure 2a** shows the data separated out by in row tree spacing treatment. These data suggest that the effect of the different tree spacings can largely be explained by differences in canopy light interception. **Figure 2b** shows the data separated out by the different pruning treatments. Again, the cumulative yield differences can largely be explained by the different levels of light interception. In

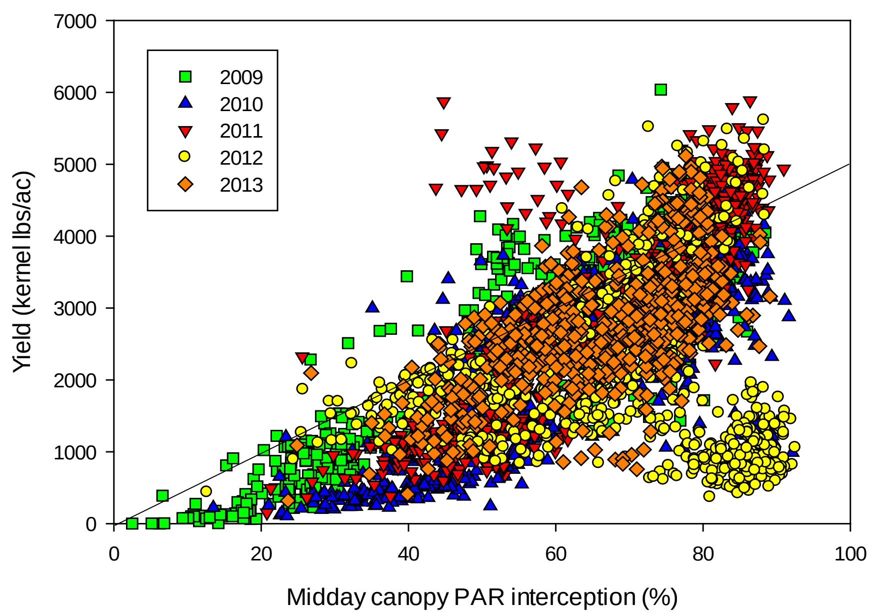

Figure 1. Midday canopy light interception versus yield relationship from mobile platform data for almond sites throughout state for 2009-2013 seasons. Solid line indicates theoretical sustainable upper limit.

general, pruned treatments tend to have lower cumulative yields for a given level of light interception due to the fact that the act of pruning generates vegetative growth that is less productive for 1-2 years following pruning.

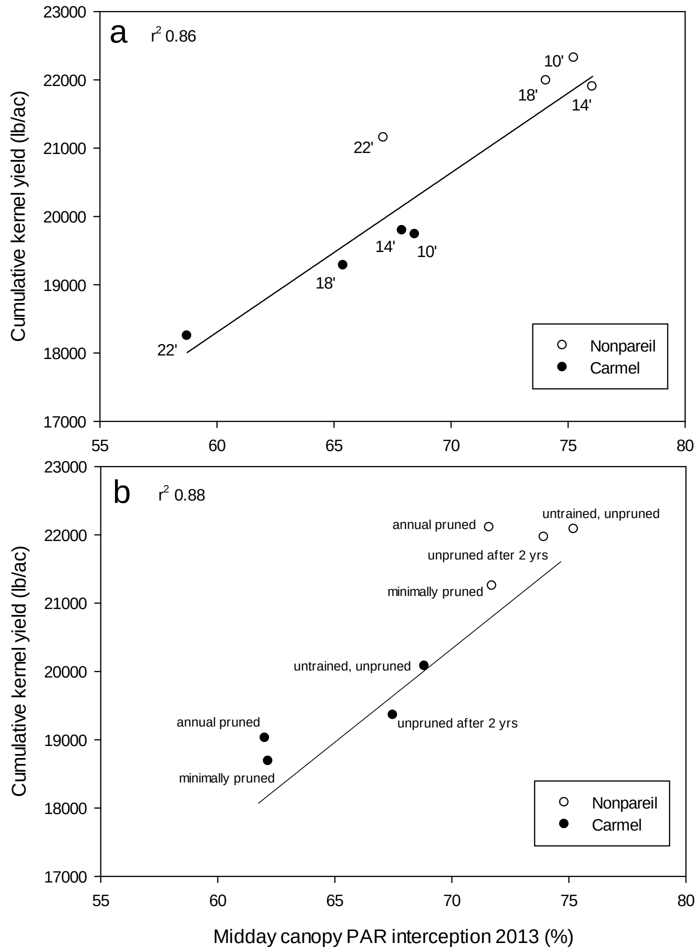

Figure 2. Midday canopy PAR interception versus cumulative yield (through year 14) by (a) variety and tree spacing and by (b) variety and pruning treatment. Trial is in Stanislaus County conducted by Roger Duncan.

The light bar data combined with the corresponding yield data allow us to look at the productivity of different cultivars or varieties as a function of both canopy size and productivity per unit light intercepted. We have not previously been able to separate out these two factors. **Table 2** shows the yield per unit light intercepted for the different.

Table 2. Yield per unit light intercepted by Nonpareil source and variety for McFarland Variety trial 2009-2013.

Variety	2009-2013 yield/PAR	2009 yield/PAR	2010 yield/PAR	2011 yield/PAR	2012 yield/PAR	2013 yield/PAR
Nonpareil-Nico	55.7 a	69.3 abcd	49.7 a	86.7 a	38.2 abc	61.6 a
Nonpareil-3-8-2-70	55.2 a	71.8 abc	47.1 ab	87.9 a	36.2 abcde	56.5 ab
Nonpareil-Newell	52.8 a	72.8 abc	45.2 abc	81.0 ab	33.4 bcde	58.0 ab
Nonpareil-Driver	55.0 a	76.1 ab	46.2 abc	84.3 a	36.6 abcde	60.2 a
Nonpareil-5	53.3 a	68.5 abcd	50.8 a	78.0 ab	34.7 abcde	55.4 ab
2-19e	52.4 a	71.6 abc	33.7 def	73.6 ab	41.8 ab	44.0 cd
Winters	52.7 a	63.8 bcde	38.5 bcde	67.3 bc	38.4 abc	50.3 bc
Kahl	53.9 a	79.2 a	43.4 abcd	59.1 cd	43.0 a	57.9 ab
Nonpareil-7	50.9 ab	.	49.4 a	76.1 ab	36.7 abcd	58.6 ab
Nonpareil-6	50.3 abc	68.9 abcd	48.7 ab	81.6 ab	32.1 cde	56.8 ab
Nonpareil-Jones	49.7 abc	63.4 bcde	43.8 abc	81.6 ab	38.2 abc	54.7 ab
Marcona	43.5 bcd	77.7 a	36.7 cdef	51.8 de	12.7 f	49.4 bc
Chips	43.2 cd	55.9 de	48.4 a	51.4 de	37.1 abcd	39.7 de
Sweetheart	37.5 de	59.6 cde	42.2 abcd	52.5 de	28.8 de	40.4 de
Kochi	33.9 e	52.6 e	23.5 g	43.4 e	28.2 e	33.5 e

Nonpareil sources as well as the varieties included in a variety trial near McFarland, CA for the 2009-2013 seasons. For the 5 year average data, there was not a significant difference in yield per unit light intercepted among the Nonpareil sources. Among the pollenizers, only Kahl, selection 2-19e and Winters had equivalent yield per unit light intercepted compared to Nonpareil sources. The large fluctuations in the yield per unit light intercepted (particularly notice 2011 versus 2012 values) suggest that multiple year light interception and yield data are essential to examine treatment or variety yield impacts. Although there were no significant differences in yield per unit light intercepted among the Nonpareil sources, there were significant differences in cumulative yield (see annual report for Field Evaluation of Almond Varieties [13-HORT2-Lampinen/Haviland] for details). This could be due to small differences in light interception each year adding up to a significant effect on cumulative yield over time.

Another potential use of these data is to look at the effects of different fumigation treatments on productivity based on separating out canopy size effects from effects of productivity per unit light intercepted. It is clear from these data that different fumigants can have an effect on yield by influencing canopy size as well as by influencing productivity per unit canopy light intercepted since some treatments led to both smaller tree size and less productivity per unit light intercepted (see 12-HORT13-Lampinen for data). It is possible that the lower productivity per unit light intercepted is a result of pruning since growers tend to prune smaller trees more vigorously.

Leaf temperature measurements along with microclimatic data have been found to be very useful for prediction of plant water stress and for development of stress indices such as crop water stress index (CWSI) in many crops. In this study, a hand-held sensor suite (HHSS) was developed to measure leaf temperature, air temperature, relative humidity, photo synthetically active radiation (PAR), and wind speed. The HHSS was very convenient to use in field conditions and was successfully evaluated in commercial orchards in almond and walnut crops. Stepwise multiple linear regression models were produced to relate leaf temperature with plant water status and micro-climatic data with coefficient of determination values of 0.88 and 0.83 for almond and walnut crops respectively. These models were validated to classify the trees into water stressed and not-stressed categories with critical error of misclassification of 1.6 and 2.7% in almond and walnut crops, respectively. In another experiment, a infra-red thermal camera was used to capture images of almond and walnut tree canopies and leaf temperature was also measured by HHSS simultaneously. Leaf temperature data measured with HHSS was used to validate the performance of infra-red thermal camera for measuring shaded canopy temperature. Three different techniques were used to extract shaded canopy temperature from thermal images. Raw image analysis, unsupervised classification using k-means, and supervised classification using microclimatic data were conducted and results were compared with HHSS measured leaf temperature in all cases. Supervised classification using HHSS data produced the best result compared to other analysis techniques.

Objective 2 - The sensor suite (**Figure 3**) was successfully evaluated in three crops (almonds, walnuts and grapes) for both sunlit and shaded leaves. Stepwise linear regression models developed for shaded leaf temperature yielded coefficient of multiple determination values of 0.88 for almond. An infra-red thermal camera was used to capture images for comparison measurements of shaded leaf temperature. Stem water potential (SWP) and air temperature (T_a) were found to be significant variables in all models. Regression models were used to classify trees into stressed and unstressed categories with critical misclassification error (i.e., predicting a stressed tree as unstressed) for sunlit and shaded leaf models of 8.8% for almond.

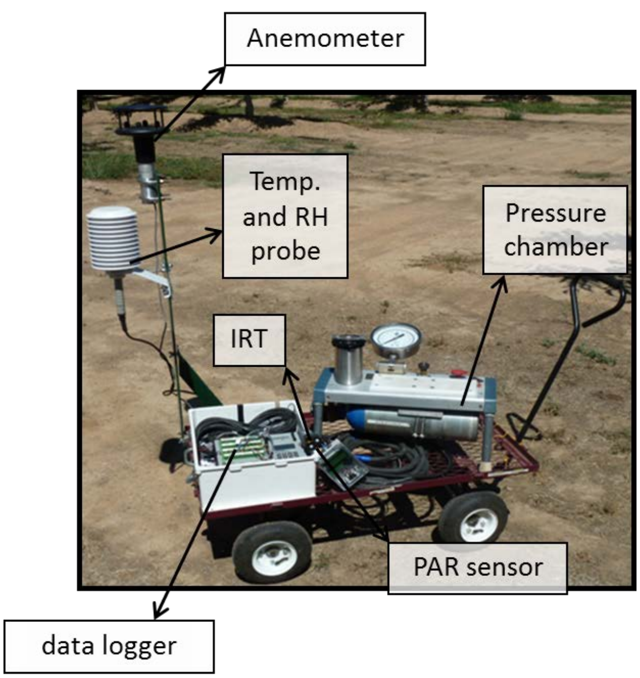

Figure 3.. Mobile sensor suite.

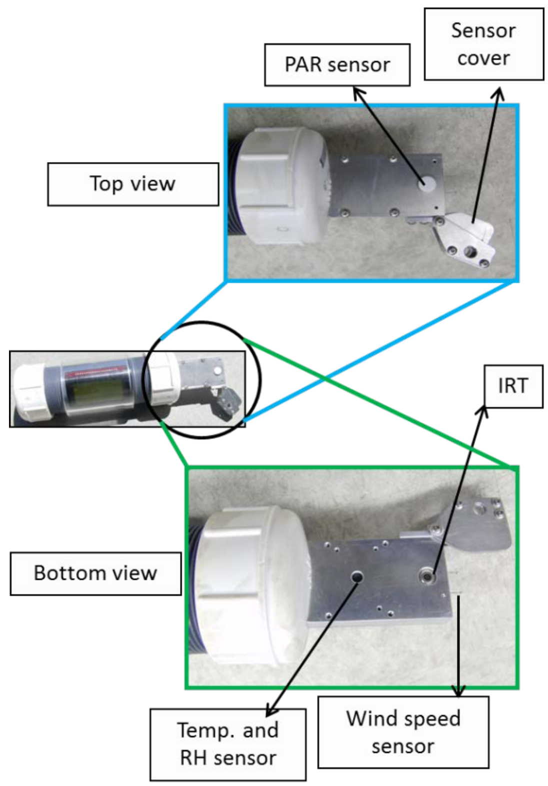

Figure 4. 2nd generation hand-held sensor suite

The results suggest it is feasible to use the sensor suite to determine plant water status for irrigation management for almond. However, regression models were found to be specific to the time during the season, and the mobile sensor suite system cart was bulky to take in the orchard for frequent data collection. Based on these observations, a much more compact sensor suite was developed and tested (**Figure 4**). This unit is convenient to use and it measures leaf temperature and microclimatic variables using similar sensors as were used in the mobile sensor suite except the sensors are miniaturized. This handheld unit is working well. Data from this device is shown in **Figure 5**. The sensor suite is described in more detail in the publication by Dhillon et.al (2014) listed at the end of this report.

Development and testing of the continuous leaf monitor continued in 2013-14. A modified crop water stress index (MCWSI) was developed to deal with variability in baseline values over the course of the measurement period. Data were analyzed using the SAS statistics package (SAS Institute, Inc. v.9.3 Cary, NC). Data corresponding to 10:00AM to 4:00PM were selected and the moving average for four data points was used for smoothing. Trees were irrigated at night and data from the first or second day after irrigation were considered as fully watered conditions since the pressure chamber

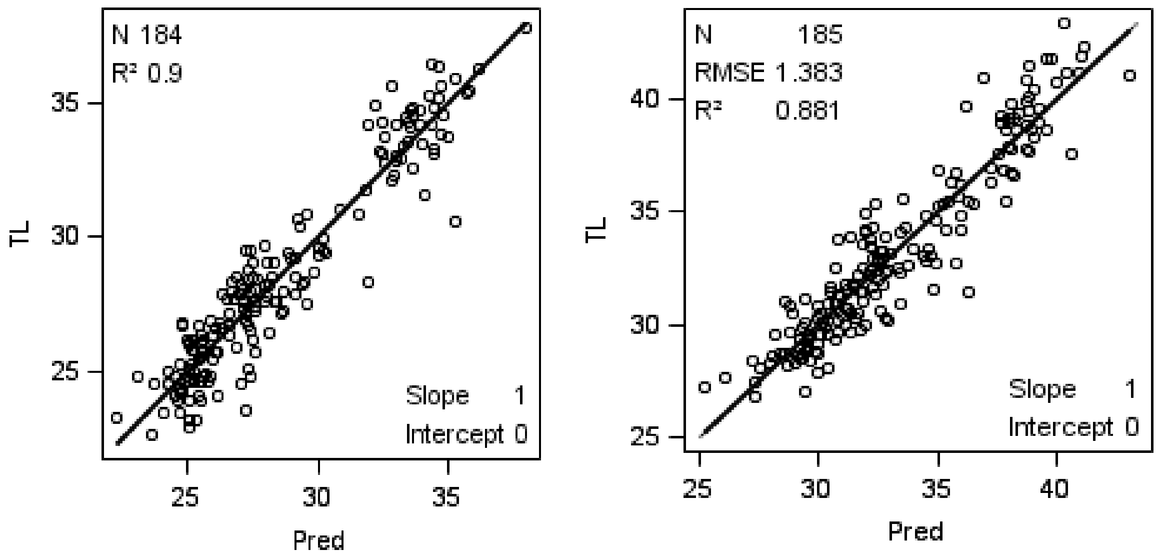

Figure 5. Multiple linear regression data comparing predicted to measured leaf temperature (using the new sensor suite) for (a) shaded and (b) sunlit almond leaves.

data indicated that some trees were taking two days to totally recover from water stress following an irrigation event. The purpose of the 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 well-watered baseline was updated after every irrigation event; this was called Modified Crop Water Stress Index (MCWSI).

Figure 7a shows air temperature data measured by leaf monitors over a week in the orchard. **Figure 7b** shows the typical pattern of leaf to air temperature difference (T_{air} – T_{leaf}) data. As expected temperature difference is close to zero at night since there is negligible transpiration. As the sun rises the leaf starts transpiring which results in the leaf being cooler than the air.

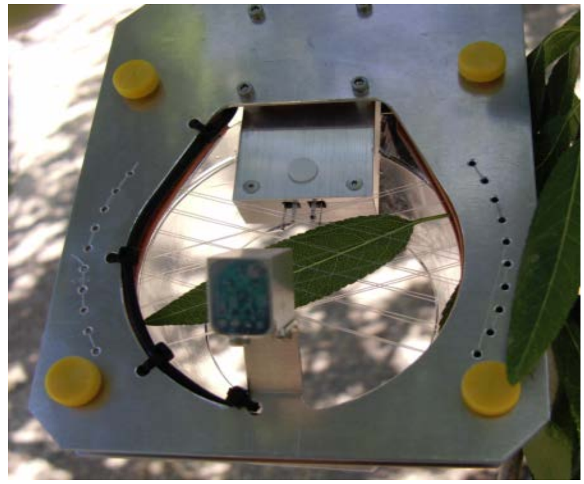

Figure 6(a): Leaf monitor installed in almond.

Figure 6(b): Close up of leaf monitor installed on almond leaf.

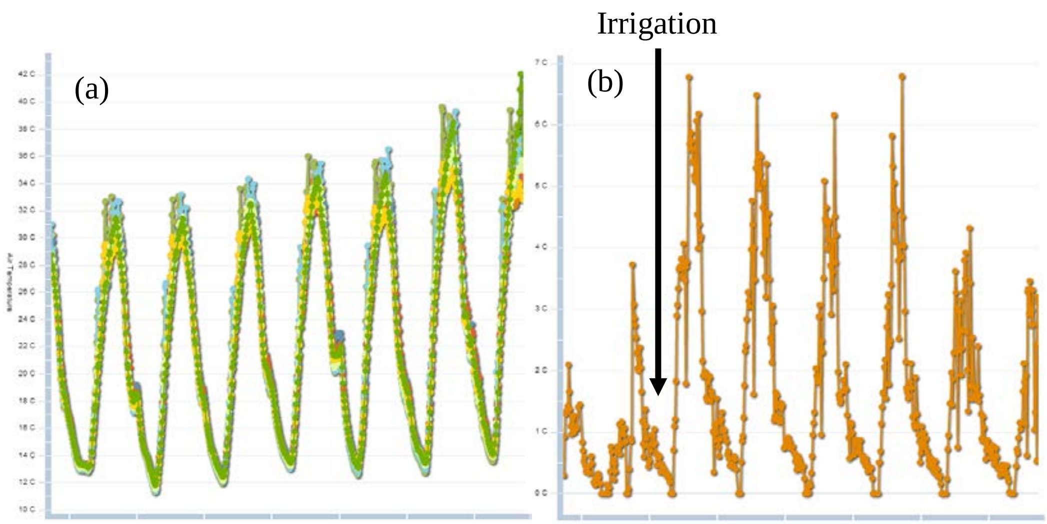

Figure 7: Screen shots of the continuous leaf monitor (a) air temperature (^{0}C) and (b) leaf to air temperature difference (T_a – T_L) for an almond leaf for eight consecutive days with an irrigation event indicated.

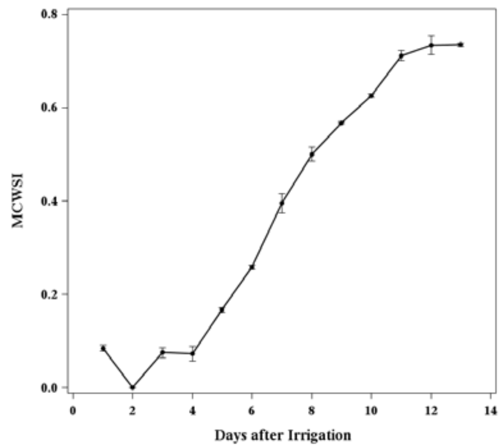

Figure 8: Typical pattern of modified crop water stress index after an irrigation event for an almond tree.

Figure 8 shows the pattern of water stress detected by the continuous leaf monitor following an irrigation event. The continuous leaf monitor appeared to track the development of stress following an irrigation event well suggesting it may be a useful tool for growers continuous monitoring of stress.

Objective 3- An iPhone application to estimate canopy light interception and PAR interception in walnut and almond is currently in development. The user takes a picture of the orchard floor shadows projected by the canopy, and selects the area to make the estimate of light interception (usually either one or two trees down the row). The application estimates the canopy light interception using images of the canopy ground shadow, as shown in **Figure 9.** The iPhone app then corrects the image for perspective, converts the area of interest into either shadow or sun and then tabulates the pixels of each (**Figure 10**). The estimation with the iPhone app is about plus or minus 5% accuracy compared to the mobile platform light bar data. When branches or leaves

Figure 9. Photo showing the angle of view required by the application to estimate the canopy light interception.

hang into the view of the shadow image on the ground, the deviation can be higher. This can be corrected by taking the images from a lower angle, but the image will have less accuracy in the back of the scene due to the narrow angle with the ground.

Figure 10. Image showing the image corrected for perspective with the estimated midday canopy light interception shown.

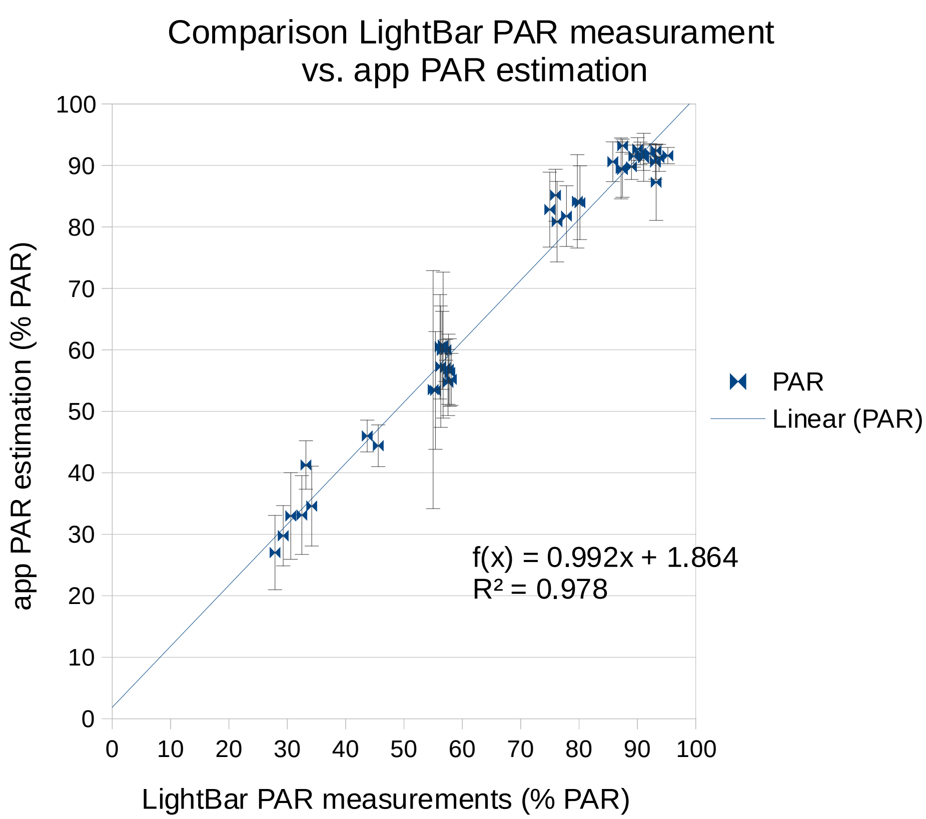

Figure 11. Comparison between the mobile platform light bar PAR and the iPhone app PAR estimation.

The application has been calibrated for almonds and the results are promising as it is shown in **Figure 11**. A more detailed calibration is being done with pictures taken by the GoPro camera on the mobile platform light bar as well as using the iPhone camera in different orchards across California in 2014. This new set will be used to evaluate whether or the calibration varies over the growing season.

Preliminary Conclusions:

Data on midday canopy light interception collected with the modified mobile platform suggests that there are a number of potential uses for this technology. The first is for providing a baseline for assessing how an orchard is performing relative to other orchards of similar age and variety. Another is for separating out the effects of rate of canopy growth from productivity per unit canopy light intercepted in different clones or varieties. A third potential use is for assessing the efficacy of different fumigants by again separating out the effects of canopy size from productivity per unit light intercepted. Additional investigations using this technology include looking at the effect of tree spacing and orchard age on productivity per unit light intercepted. This technology also allows the elimination of canopy size differences from any type of research trial. These data are being used in a wide range of almond research project statewide. Two publications describing the mobile platform light bar are listed at the end of the report.

A second generation more compact, mobile sensor suite as well as a leaf temperature monitor were developed and evaluated to predict plant water status by measuring the leaf temperature of almond trees. The compact sensor suite consists of an infrared thermometer to measure leaf temperature along with relevant sensors to measure microclimatic variables. See publication by Dhillon et.al. (2014) listed at the end of this report for details on the sensor suite. The compact sensor suite was successfully evaluated in almond on sunlit and shaded leaves. The results suggest that it is feasible to use the sensor suite to determine plant water status for irrigation management of almond. In addition to the compact sensor suite, a leaf monitor was developed that can be used to continuously monitor leaf temperature of a shaded leaf. Refinement of the device was completed in 2013-2014. The leaf monitor is able to track almond tree water stress over an irrigation cycle with the results comparing well with midday stem water potential measurements using the plant pressure chamber suggesting the device could be used for continuous monitoring of plant water status. Results from the 2014 season will be used to further refine the device. UC Davis has applied for a patent on this device.

A preliminary working version of the iPhone application for estimating midday canopy light interception was tested in 2013-14. A near final version will be deployed in the field during August 2014. Testing with farm advisors and growers is planned for the summer of 2015.

Research Effort Recent Publications:

Journal

Lampinen, Bruce.D., Vasu Udompetiakul, Gregory T. Browne, Samuel G. Metcalf, William L. Stewart, Loreto Contador, Claudia Negron, and Shrini K. Upadhyaya. 2011. A mobile platform for measuring canopy photosynthetically active radiation interception in orchard systems. HortTechnology 22(2): 237-244.

Bruce Lampinen, Shrini Upadhyaya, Vasu Udompetaikul, Greg Browne, Jed Roach, Samuel Metcalf, William Stewart, Loreto Contador, Claudia Negron, Ignacio Porris Gómez, Bob Beede, Carolyn DeBuse, David Doll, Roger Duncan John Edstrom, Rachel Elkins Elizabeth Fichtner, Joe Grant, Janine Hasey, Brent Holtz, Kathy Kelley, Bill Krueger, Franz Niederholzer, and Jeff Olson. 2014. A second generation mobile platform for assessing midday canopy photosynthetically active radiation interception in orchard systems. Acta Hort. In Press.

Dhillon, R., V. Udomptetaikul, F. Rojo, J. Roach, S. Upadhyaya, D. Slaughter, B. Lampinen and K. Shackel. 2014. Detection of plant water stress using leaf temperature and microclimatic measurements in almond, walnut and grape crops. Vol. 57(1): 297-304.

Abstracts

Roja, Francisco, Rajveer Dhillon, Shrinivasa Upadhyaya, Bryan Jenkins, Bruce Lampinen, Jedediah Roach, Kellen Crawford, and Samuel Metcalf. 2014. Modeling light interception for estimating yield in almond and walnut trees. 12th Int. Conf. on Prec. Ag., July 20-23, 2014, Sacramento, CA.

Zarate-Valdez, Jose.L., Margarita Huesca, Michael L. Whiting, Bruce D. Lampinen, Alicia Palocios-Orueta and Susan L. Ustin. 2014. Intensive ground sampling of canopy light-capture for modeling California nut yields for growers and regional satellite predictions. 12th Int. Conf. on Prec. Ag., July 20-23, 2014, Sacramento, CA.