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

Project No.: **11-HORT13-Lampinen**

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Objectives:

Objective 1) The first aspect of this project involves updating and retrofitting a Kawasaki Mule (**Figure 1**) with a new, more robust and adjustable lightbar support structure as well as sensors designed to develop the ability to detect water stress in trees.

Objective 2) The second component of this project involves using the Mule mounted lightbar setup 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 4**).

The data from the Mule lightbar are of use for any studies that aim to quantify the impact of treatments on yield. By measuring canopy light interception on a large scale, the impacts of differences in canopy development can be separated out from other treatment impacts allowing much more robust data interpretation.

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. In 2011, the sensor suite was upgraded with a more precise infrared thermometer to make it easier to assure the target being measured. Measuring leaf temperature using an IR spot sensor or 2D imagery while accounting for windspeed, leaf orientation, and incident PAR can provide a potential means of detecting plant

water status. We describe the development of a sensor fusion technique to detect plant water stress in which we look at the leaf temperature using an IR sensor, incident PAR using our PAR measurement system, color image (RGB) for leaf inclination information, and a wind speed sensor. Another season of data was collected with the second generation portable sensor suite. This sensor suite was used to measure leaf temperature, light intensity, air temperature, air humidity, and wind speed in almond trees with different levels of stem water potential. Results from the 2011 season continued to suggest that this technique can be used to predict stem water potential, and that shaded leaves may work better than sunlit leaves. Adapting this sensor suite to the mobile platform presents some challenges but the ability to use shaded leaves will make it somewhat easier.

Data collected by the authors over the past several years has provided a rough upper limit to productivity in walnut and 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 recently outfitted a Kawasaki Mule with a light bar that is able to measure light across an entire row (up to 28 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. 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 if 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.

Materials and Methods:

<u>Objective 1)</u> Mule platform modification: The existing Mule mounted lightbar setup (**Figure 1a**) was modified to make it more robust and adjustable to a wider range of tree spacings. This included rebuilding the entire light bar with a more stable and more adjustable base, and a built-in protective bumper to push low hanging branches up and over the lightbar (**Figure 1b**). A more accurate global positioning satellite (GPS) receiver and an encoder that measures distances using the rotation of the axle were added to provide more accurate positional information. In addition, three infrared thermometers with a narrower angle of view were added for measuring soil surface

temperature under the tree canopy of both the left and right side of the light bar as well as in the middle of the drive row. This allows us to assess soil temperature data beneath varieties in an almond orchard separately.

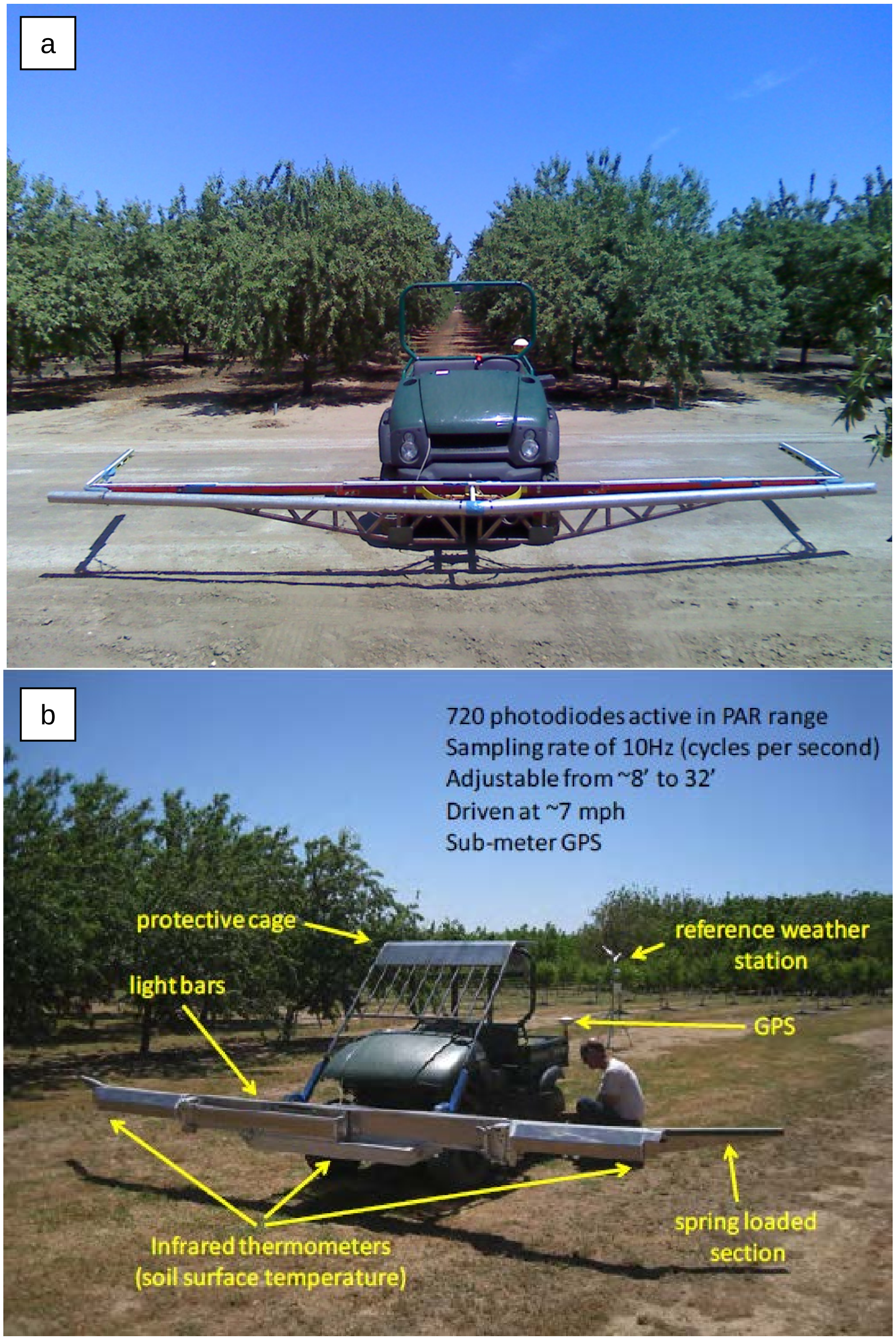


Figure 1. (a) Design of Kawasaki Mule mounted lightbar as used during summer 2010. Modifications included adding a branch bumper on front designed to aid in pushing through orchards with many low overhanging branches. (b) Over the winter of 2010-11, the entire lightbar was redesigned and rebuilt and made much more protected, robust and adjustable

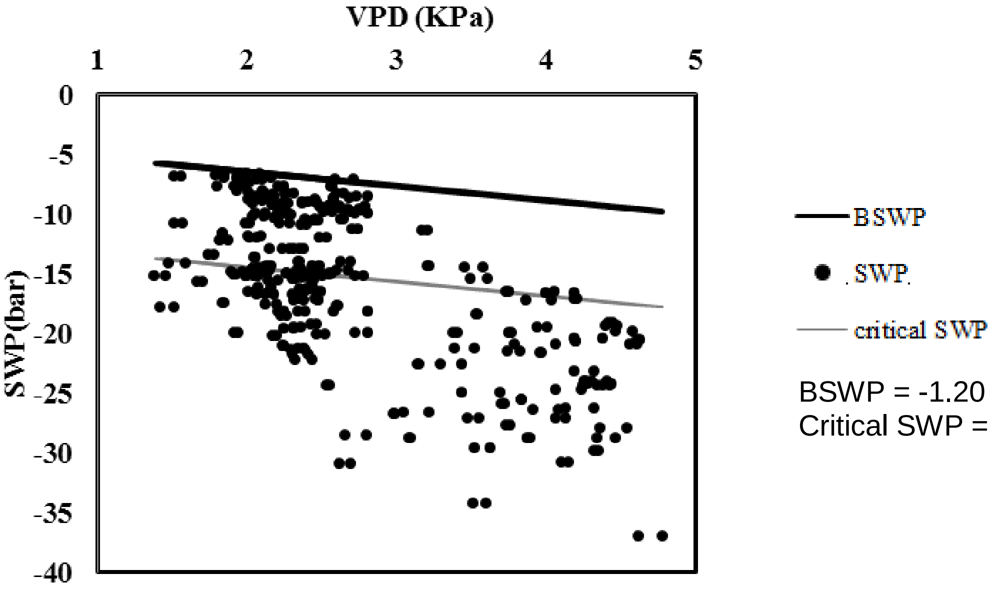
The mobile sensor suite was modified to make it more accurate by adding a more narrowly focused infrared leaf temperature sensor (6000L, Everest Interscience, Tucson, AZ). The suite also had three additional sensors for measuring other relevant environmental parameters including photosynthetically active radiation (PAR) using a PAR sensor (LI-190, LICOR inc., Lincoln, NE), air temperature and humidity using an air temperature and humidity probe (HMP35C, Visalia Inc., Woburn, MA) and wind speed around the tree canopy using an anemometer (WindSonic, Gill Instruments Ltd., Hampshire, UK). The sensor suite with all its components is shown in **Figure 2**. Standard pressure chamber (**Figure 2**) measurements were taken for validation of sensor suite measurements. A data logger (CR3000 micrologger, Campbell scientific Inc., Logan, UT) was used to acquire and store data for all the sensors.

Figure 2. Mobile sensor suite and pressure chamber during data collection in an almond orchard.

Almond trees were subjected to different stress levels to cover normal range of water stress levels encountered. The orchards were visited multiple times throughout the season to collect data. During each visit, mid-day stem water potential of each tree was measured using the pressure chamber (**Figure 2**) and simultaneously leaf temperature, air temperature, relative humidity, wind speed, and PAR data were recorded using the sensor suite for 10 leaves/tree within a time span of 5-10 minutes. Half of the leaves studied were sunlit and half were shaded leaves.

The ultimate goal of developing the sensor suite was to predict real-time plant water status by measuring leaf temperature and microclimatic information and to then classify the trees into stressed or unstressed categories so that this information can be used to implement variable rate irrigation management. In this study, data obtained from the sensor suite and pressure chamber were analyzed using the SAS software package (SAS Institute, Inc. v.9.2. Cary, NC) to develop regression models for leaf temperature as the dependent variable. By utilizing stepwise model selection approach with k-fold cross validation (SAS, 2010), empirical models for leaf temperature as functions of SWP, PAR, air temperature, RH, and wind speed were developed for almond for sunlit and shaded conditions. A second order polynomial model was used to account for quadratic effects, if any. We also developed a technique to classify the plant water status as stressed or unstressed based on critical values of stem water potential. The prediction models were used to determine critical values of the leaf temperature (T_L^c) corresponding to critical values of stem water potential (SWPc). Plants were classified as stressed if leaf temperature T_L was higher than T_L^c. Classification accuracy was verified by comparing predicted stress to the measured stress level.

Actual tree stress level was defined by considering the plant water potential below the baseline, which is maximum SWP achieved when plant gets fully irrigated. This baseline depends on crop type and vapor pressure deficit. Baseline functions (BSWP) for almonds are those developed by McCutchan and Shackel (1992) and Shackel (1997) and are shown in **Figure 3** with their respective critical SWP and measured pressure chamber SWP data. The plant stress threshold was defined as a straight line parallel to the baseline (**Figure 3**). In our study, the plant stress threshold was placed under the baseline by 8 bars for almond.



BSWP = -1.20 VPD – 4.10
Critical SWP = BSWP – 8

Figure 3. Baseline and critical SWP for almond used for classification analysis.

Objective 2) Data for light interception and yield was used to refine the relationship shown on the graph in **Figure 4**. Because the data in **Figure 4** was collected with a hand lightbar and the yield and light interception areas were not always equal, there is quite a bit of variability in the data. With a better estimate of the maximum productivity per unit light intercepted that can be obtained with measuring yield from same areas measured with the Mule light bar, these data can be used to assess potential orchard yield and will allow us to separate out canopy light interception as a variable in other research projects. These data are being used to evaluate pruning trials to separate the effect of the pruning treatment on overall canopy light interception as opposed to the effect of the pruning treatment on productivity per unit canopy. It is also being used to allow block to block variability to be assessed before or after a research trial is initiated. These data are also being used to look at how much of the variability in yields across an individual orchard is due to differences in canopy light interception as compared to other factors. The measurements also can be used to evaluate productivity of new almond selections compared to existing cultivars. In the future, these data will allow any orchard to be evaluated as to how well it is producing compared to other orchards of similar canopy cover. This will allow a grower to assess how current management practices are impacting productivity per unit canopy light intercepted.

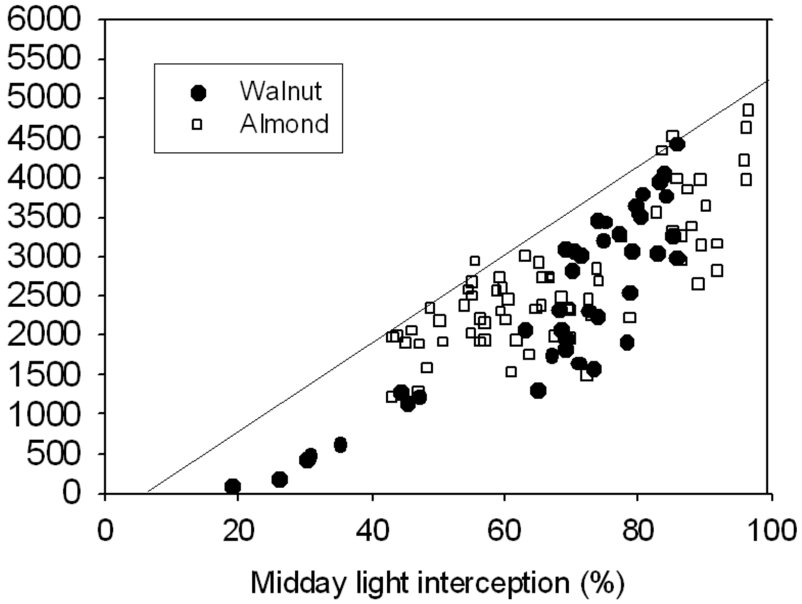


Figure 4. Midday canopy light interception versus yield relationship from various almond and walnut trials from throughout the state using hand lightbar.

Refine light interception/yield relationship in almond. Nineteen almond orchard sites of varying ages and varieties from throughout the almond growing area of California were selected for measurements in 2011(**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. 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 time

Table 1. Almond orchards sites mapped with Mule lightbar during 2011 season.

Site #	County	Trial	Date mapped
1	Kern	Spur Dynamics	06/08/11
2	Kern	McFarland Variety trial	06/10/11
3	Madera	Paramount New Columbia main fumigation trial	06/18/11
4	Madera	Madera Growers South	06/19/11
5	Madera	Agriland irrigation trial	06/20/11
6	Colusa	Nickels almond pruning/training trial	06/25/11
7	Madera	Agriland fumigation trial	06/26/11
8	Kern	Belridge spur survival	06/27/11
9	Kern	SCRI-Belridge continuous fertigation	08/28/11
10	Kern	SCRI-Belridge	06/30/11
11	Madera	Paramount New Columbia fumigation/irrigation trial	07/04/11
12	Colusa	Nickels organic almond	07/07/11
13	Colusa	Nickels almond rootstock	07/08/11
14	Colusa	Shackel almond deficit trial	07/18/11
15	Stanislaus	Duncan almond pruning, spacing and training trial	07/22/11
16	Glenn	Erickson	07/31/11
17	Colusa	LeGrande Freshwater orchard	08/08/11
18	Colusa	LeGrande	08/09/11
19	Merced	Browne Frago trial	08/31/11

measurements 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 USDA 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.

Results and Discussion:

Objective 1) The modifications to the mobile platform to make it more robust and adjustable worked well (**Figure 1**). The new structure is substantially more stable and able to withstand the rough environment in minimally pruned orchards well. The finer level of width adjustment means that the lightbar can be more accurately set to measure each individual orchard width. The more accurate global positioning satellite (GPS) receiver is giving good results even in heavily canopied orchards which have been problematic in the past. The addition of an encoder that measures distances using the rotation of the axle allows a second, accurate check on position in the orchard. In addition, the three infrared thermometers with a narrower angle of view allow measurement of surface temperature under the variety on each side of the light bar as well as in the middle of the drive row.

The mobile sensor suite was extensively tested in almonds in 2011. The tests revealed that the sensor suite can be used to detect midday stem water potential in almond. The stepwise selection based multiple linear regression (MLR) models yielded coefficient of multiple determination values of 0.76 for sunlit leaves and 0.79 when shaded leaf temperature was used to develop the model. Moreover, two classification techniques (Stepwise discriminant analysis (SDA) and Canonical discriminant analysis (CDA)) were used to identify stressed and unstressed trees. When these three methods (MLR, SDA, and CDA) were used for plant water stress classification (as stressed and unstressed) we found that: in almonds, critically wrong errors (i.e., stress trees being classified as unstressed trees) were 8.1, 8.8, and 9.0% respectively for MLR, SDA, and CDA methods. Over-irrigation errors (i.e., unstressed trees being classified as stressed trees) were 10.6, 5.5, and 8.0% respectively for MLR, SDA, and CDA methods. When the spatial variability in stressed versus unstressed conditions was mapped, all three techniques yielded similar results.

One major issue that was observed during these tests was that the calibration equation was influenced by the seasonal timing of measurement (i.e., calibration equation developed at the beginning of the season did not apply well for the end of season data). Moreover, the sensitivity of the inexpensive thermal IR sensor used in this study was also a concern (± 0.5 °C). We decided to address these two issues more thoroughly during the 2012 growing season. To address the sensitivity issue, we have developed a multiple (9) IR sensor head unit. This unit should reduce the instrument noise by a factor of three. We have also developed a leaf monitor to continuously measure leaf temperature to address the issue of temporal changes in the calibration. Both of these units are being used in the field in 2012 to address these issues. Based on the outcome of this year's results, we will decide if there is a value to retrofit the sensor suite to the mule as originally proposed or if we should concentrate on developing an inexpensive leaf monitoring system.

Objective 2) Data collected with the Mule lightbar in 2011 from orchards listed in **Table 1** are shown in **Figure 5**. Although many orchards produced yields well above the sustainable upper limit line in 2009, in 2010 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.

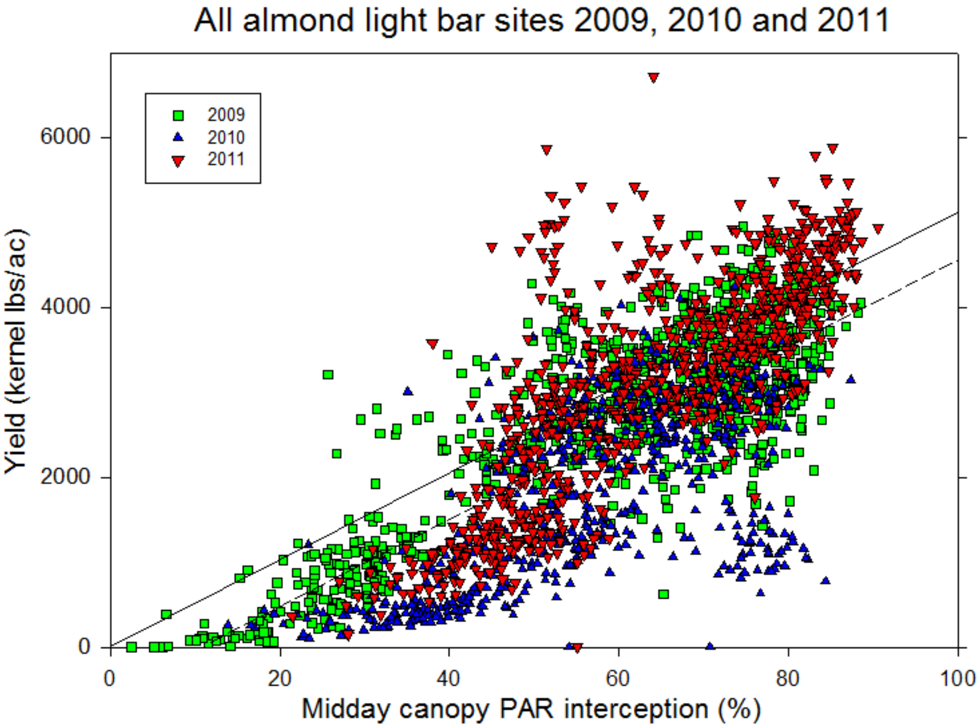


Figure 5. Midday canopy light interception versus yield relationship from mobile platform data for almond sites throughout state for 2009 and 2010 seasons. Solid line indicates theoretical sustainable upper limit while dashed lines indicate regression line

The data collected with the mobile lightbar has many potential uses. One use is 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 light interception, yield per unit light intercepted and kernel yield for the different Nonpareil sources as well as the varieties included in a variety trial near McFarland, CA. As of 2011, the midday canopy light interception is not significantly different among the Nonpareil sources and pollenizers (**Table 2**). However, it now appears that differences in yield per unit light intercepted may be occurring with the Nonpareil sources generally showing higher yield per unit light intercepted compared to the pollenizers. To separate out the small potential differences among the Nonpareil sources we will have to look at least one more year of data to eliminate alternate bearing effects, etc.

Table 2. Midday canopy light interception, yield per unit light intercepted and yield per acre by Nonpareil source and variety for McFarland Variety trial 2011.

2011		**Kernel pounds per**	
Variety	**Midday canopy PAR interception (%)**	**unit PAR int.**	**Acre**
Nonpareil-Nico	63.5 a	90.1 a	4964 a
Nonpareil-3-8-2-70	60.2 a	79.5 ab	4962 a
Nonpareil-Newell	70.2 a	69.4 abc	4745 a
Nonpareil-Driver	66.7 a	72.8 ab	4683 a
Nonpareil-7	65.1 a	72.3 ab	4555 a
Nonpareil-5	63.5 a	70.2 abc	4342 a
Nonpareil-6	65.5 a	74.7 ab	4619 a
2-19e	71.0 a	65.2 bcd	4460 a
Nonpareil-Jones	65.9 a	70.0 abc	4360 a
Winters	64.7 a	56.8 cde	3554 b
Sweetheart	73.1 a	47.3 cde	3412 bc
Chips	68.5 a	44.7 de	2985 bcd
Kahl	68.5 a	45.6 de	2953 bcd
Marcona	64.9 a	45.0 de	2746 d
Kochi	72.5 a	39.4 e	2825 d

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. An example of this is shown in **Table 3**. It is clear from these data that different fumigants can have an effect on yield by influencing canopy size but also by influencing productivity per unit canopy light intercepted. This can be seen in that some treatments led to both smaller tree size and less productivity per unit light intercepted. However, it is possible that this is actually a result of pruning since growers tend to prune smaller trees more vigorously.

Preliminary Conclusions:

A mobile sensor suite was developed and evaluated to predict plant water status by measuring the leaf temperature of almond trees. It consists of an infrared thermometer to measure leaf temperature along with relevant sensors to measure microclimatic variables. The sensor suite was successfully evaluated in almond on sunlit and shaded leaves. Stepwise linear regression models developed for sunlit leaves yielded coefficient of determination values of 0.76 and for shaded leaves 0.79. 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. Critical misclassification error (classifying a stressed tree as unstressed) for sunlit and shaded leaf models were 8.1, 8.8 and 9.0% respectively for MLR, SDA and CDA methods for almonds. These results suggest that it is feasible to use the sensor suite to determine plant water status for irrigation management of almond. However, there are still many difficulties in putting the sensor suite on to the mobile platform. A decision will have to be made whether it is better to develop a scaled down version of the sensor suite for estimating individual tree water status or whether an effort should continue to adapt it to the mobile platform.

Table 3. Midday canopy light interception, kernel yield and yield per unit light intercepted by fumigation treatment and coverage, Madera County methyl bromide alternatives site 2009, 2010 and 2011.

2009

Fumigant, lbs per treated area	Treated area in tree row (and % of orchard area treated)	Fumigant per orchard acre (lbs)	2009 Midday canopy light interc. (%)	2009 Yield (kernel lbs/acre)	2009 yield per unit light intercepted
Control	8-ft strip (38%)	0	12.2 e	161 d	12.1 cd
MB, 400	8-ft strip (38%)	152	15.1 de	455 cd	25.7 b
Telone II, 350	8-ft strip (38%)	133	17.7 cd	547 bc	28.6 b
CP, 400	8-ft strip (38%)	152	24.3 ab	932 a	38.2 ab
CP, 300	8-ft strip (38%)	114	23.5 ab	975 a	42.2 a
CP, 200	8-ft strip (38%)	76	26.8 a	979 a	37.2 ab
CP, 400	8x8-ft tree sites (17%)	68	24.3 ab	811 ab	36.9 ab
IM:CP 50:50, 300	8-ft strip (38%)	152	25.6 ab	948 a	37.4 ab
Telone C35, 550	8-ft strip (38%)	209	24.4 ab	905 ab	37.1 ab
Telone C35, 550	8x8-ft tree sites (17%)	93	21.6 bc	778 abc	36.1 ab
Telone C35, 550	Broadcast (100%)	550	25.5 ab	941 a	36.6 ab
Pic-clor 60, 550	8-ft strip (38%)	209	26.3 ab	1123 a	43.2 a
Pic-clor 60, 300	8-ft strip (38%)	152	25.7 ab	834 ab	32.5 ab

2010

Fumigant, lbs per treated area	Treated area in tree row (and % of orchard area treated)	Fumigant per orchard acre (lbs)	2010 Midday canopy light interc. (%)	2010 Yield (kernel lbs/acre)	2010 yield per unit light intercepted
Control	8-ft strip (38%)	0	46.1 bc	695.4 e	14.9 d
MB, 400	8-ft strip (38%)	152	45.7 c	822.3 de	17.7 cd
Telone II, 350	8-ft strip (38%)	133	49.6 abc	969.5 cd	19.5 bc
CP, 400	8-ft strip (38%)	152	54.1 a	1155.7 abc	20.6 abc
CP, 300	8-ft strip (38%)	114	51.1 abc	1154.2 abc	22.5 ab
CP, 200	8-ft strip (38%)	76	54.3 a	1329.2 ab	24.6 a
CP, 400	8x8-ft tree sites (17%)	68	50.9 abc	1128.5 abc	22.3 ab
IM:CP 50:50, 300	8-ft strip (38%)	152	56.6 a	1172.2 abc	20.6 abc
Telone C35, 550	8-ft strip (38%)	209	56.0 a	1354.8 a	24.3 a
Telone C35, 550	8x8-ft tree sites (17%)	93	51.3 abc	1066.9 bcd	20.7 abc
Telone C35, 550	Broadcast (100%)	550	55.2 a	1343.4 a	24.5 a
Pic-clor 60, 550	8-ft strip (38%)	209	55.0 a	1378.8 a	25.1 a
Pic-clor 60, 300	8-ft strip (38%)	152	53.1 ab	1297.9 ab	24.4 a

2011

Fumigant, lbs per treated area	Treated area in tree row (and % of orchard area treated)	Fumigant per orchard acre (lbs)	2011 Midday canopy light interc. (%)	2011 Yield (kernel lbs/acre)	2011 yield per unit light intercepted
Control	8-ft strip (38%)	0	58.7 ab	2168 d	36.7 bcd
MB, 400	8-ft strip (38%)	152	53.8 bc	2089 d	38.4 bcd
Telone II, 350	8-ft strip (38%)	133	58.2 ab	2480 bcd	42.8 bcd
CP, 400	8-ft strip (38%)	152	60.7 ab	2588 abcd	42.7 bcd
CP, 300	8-ft strip (38%)	114	56.2 ab	2596 abcd	46.3 abc
CP, 200	8-ft strip (38%)	76	61.0 ab	2621 abcd	43.0 bcd
CP, 400	8x8-ft tree sites (17%)	68	58.2 ab	2734 abc	47.1 abc
IM:CP 50:50, 300	8-ft strip (38%)	152	62.2 a	2987 ab	48.2 ab
Telone C35, 550	8-ft strip (38%)	209	61.7 a	2852 abcd	44.5 bcd
Telone C35, 550	8x8-ft tree sites (17%)	93	59.3 ab	2639 abcd	44.5 bcd
Telone C35, 550	Broadcast (100%)	550	61.1 ab	3079 a	50.4 ab
Pic-clor 60, 550	8-ft strip (38%)	209	60.4 ab	3038 ab	50.4 ab
Pic-clor 60, 300	8-ft strip (38%)	152	59.2 ab	2633 abcd	44.6 bcd

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.

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