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

Project No.: **10-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 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**).

Measuring this type of data is 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.

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 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.

Preliminary results suggest that 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. Ondimu (2007) found that a combination of a thermal image with a Red-Green-Blue (RGB) color image was able to account for moss temperature, texture and color, as well as predict water stress. We describe the use 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.

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.

Preliminary data has also been collected with a portable sensor suite consisting of an infrared thermometer and sensors for relevant ambient conditions. 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 2010 season 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.

Materials and Methods:

Objective 1. Mule platform modification: The existing Mule mounted lightbar setup (**Figure 1a**) has been modified in order to make it more robust and adjustable to a wider range of tree spacings. This included rebuilding the entire light bar with a much 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 much narrower angle of view were added for measuring soil surface temperature under the tree canopy from both the left and right side of the light bar as well as in the middle of the drive row.

Objective 2. A sensor suite was developed to study the relationship between leaf temperature and plant water status. 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, Visala Inc., Woburn, MA) interfaced to a CR3000 datalogger (Campbell Scientific Inc., Logan, UT).

A new sensor suite to measure leaf temperature and microclimatic information was developed in 2010 to study the relationship between leaf temperature along with relevant microclimate information and plant water status in almonds (**Figure 2**). It consists of an infrared thermometer (Model 6000L, Everest Interscience, Tucson, AZ), a PAR sensor (LI-190, LICOR inc., Lincoln, NE), an air temperature and humidity probe (HMP35C, Visalia Inc., Woburn, MA), and an anemometer (WindSonic, Gill Instruments Ltd., Hampshire, UK).

Figure 2. Sensor suite used to determine plant water status.

Experiments were conducted in Nonpareil almond orchards located in Yolo County near Woodland and in Colusa County near Arbuckle. In each orchard, 15 trees with various plant water deficit levels were measured several times during the 2010 growing season to test the suitability of this sensor suite to determine plant water status. During each visit to the orchard, leaf temperature, PAR, air temperature, RH, and wind speed were measured using the sensor suite on each tree. SWP was measured using a pressure chamber. IR sensor was used to measure the temperatures of five sunlit and five shaded leaves per tree. Each observation consisted of averages of 5 sample of leaf temperature (T_{leaf}), air temperature (T_{air}), PAR, RH, and wind speed (v_{air}) measurements. In addition, one stem water potential (SWP) measurement was taken per tree. This experimental procedure was repeated between 3 to 6 times for a given orchard.

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 the stem water potential. The stem water potential measurement was taken within 10 minutes of sensor suite measurements.

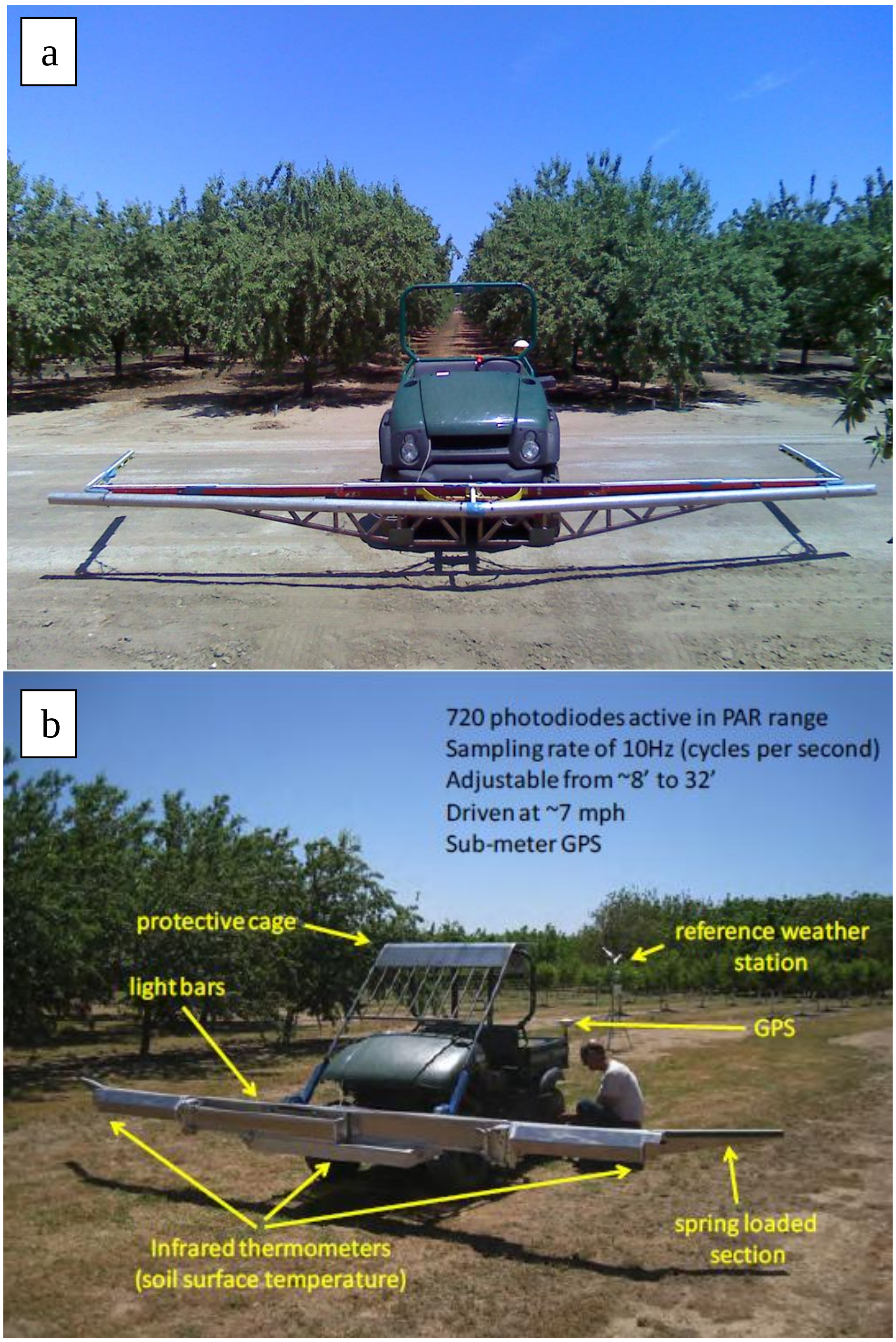

Figure 1. (a). Design of Kawasaki Mule mounted lightbar as used during summer 2010. Modifications included adding a branch bumper on front designed to aid in pushing through orchards with many low overhanging branches. (b). Over the winter of 2010-11, the entire lightbar was redesigned and rebuilt and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

The plant pressure chamber is often used to measure plant water status for irrigation management in orchard crops. It has been successfully used in almond for irrigation scheduling for many years. However, the instrument is time consuming to use, and because of this often results in an inadequate amount of sampling. Thus it is difficult to use in large-scale operations. We are investigating the use of canopy or leaf temperature as an alternative technique to determine plant water stress in almond.

<u>Objective 2.</u>

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 (**Table 1**). An emphasis was placed on

Table 1. Orchards sites mapped with Mule lightbar during 2010 season.

Site #	County	Trial	Date mapped
1	Colusa	SCRI-Arbuckle	7/8/2010
2	Colusa	Nickels almond rootstock	7/13/2010
3	Colusa	Nickels organic almond	7/12/2010
4	Colusa	Nickels almond pruning/training trial	7/12/2010
5	Colusa	Shackel almond deficit trial	7/14/2010
6	Glenn	Erickson	7/17/2010
7	Kern	McFarland Variety trial	7/28/2010
8	Kern	SCRI-Belridge	7/21/2010
9	Kern	Spur Dynamics	7/24/2010
10	Madera	Paramont New Columbia fumigation/irrigation trial	8/16/2010
11	Madera	Paramount New Columbia main fumigation trial	8/13/2010
12	Madera	Holtz almond Surround trial	8/3/2010
13	Madera	Methyl bromide grower south orchard replant site	8/8/2010
14	Madera	Agriland	8/5/2010
15	Madera	SCRI-Madera	8/4/2010
16	Stanislaus	SCRI-Salida	8/9/2010
17	Stanislaus	Duncan almond pruning, spacing and training trial	8/22/2010
18	Stanislaus	Duncan almond rootstock	8/17/2010
19	Sutter	Dejong almond model site	8/24/2010
20	Yolo	Martinez	9/14/2010

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

Results and Discussion:

<u>Objective 1.</u>

Data from the new sensor suite were analyzed using multiple linear regression (MLR) analysis, empirical models for leaf temperature (T_{leaf}) as functions of stem water potential (SWP), photosynthetically active radiation (PAR), air temperature (T_{air}), relative humidity (RH), and wind speed (v_{air}). Strong relationships between leaf temperature and stem water potential with other microclimatic information were found (equations A and B below).

This analysis showed that, data from shaded leaves (equation A, R^2=0.81) has a better relationship to the SWP than those from sunlit leaves (equation B, R^2=0.76). This is a very important and interesting outcome as sunlit leaf temperature highly depends on light interception. With high variation of leaf orientation in the tree canopy, it is hard to obtain radiation data normal to the leaf surface. Moreover, for a proximal (ground based) sensor suite, it is much more convenient to obtain shaded leaf data from below. These results suggest that future experiments should focus on shaded leaves.

Shaded leaves:

$$T_{leaf} = 29.025 + 2.100\, T_{air}^* - 0.821\, SWP^* + 0.326\, PAR^* + 0.324\, RH^* + 0.140\, v_{air}^* \qquad (A)$$

$$(R^2 = 0.8097)$$

Sunlit leaves:

$$T_{leaf} = 33.814 + 1.866\, Tair^* - 1.106\, SWP^* - 0.394\, vair^* + 0.354\, PAR^* \qquad (B)$$

$$(R^2 = 0.7605)$$

Where superscript * shows that parameters are standardized by subtracting with mean and then divided by standard deviation (**Table 2**).

Table 2. Means and standard deviations of model parameters.

Exposure	**N_{obs}**	**SWP** (bar)		**PAR** (□mol m^{-2} s^{-1})		**T_{air}** (°C)		**RH** (%)		**v_{air}** (m s^{-1})	
		Mean	*STD*	Mean	*STD*	Mean	*STD*	Mean	*STD*	Mean	*STD*
Shaded	198	-12.43	*4.54*	194.0	*37.6*	30.3	*2.2*	37.0	*6.7*	0.48	*0.22*
Sunlit	199	-12.40	*4.55*	1797.3	*170.8*	30.2	*2.3*	37.2	*6.9*	0.49	*0.24*

Further studies using discriminant analysis were performed to distinguish plants into two groups based on plant water stress - stressed and unstressed trees. Trees were defined as stressed if the SWP was lower than a baseline value of -8 bars. We used stepwise selection technique to select significant parameters. We have found that T_{leaf}, T_{air}, and RH are important parameters for stress classification (**Table 2**). However, misclassification by this technique was higher than expected. The technique resulted in 21.0% and 23.7% misclassification (**Table 3**). If we focus on misclassification of stressed trees (i.e., stressed tree classified as an unstressed tree – a critically wrong decision), the error was 15 to 16%. Another type of error for the misclassification of unstressed trees (i.e., unstressed tree classified as a stressed tree causing over-irrigation), this type of error is less critical and was 6 to 8%.

Another discriminant analysis based on canonical correlation slightly improved the critically wrong decision to about 14% (**Table 4**). However, it has a trade-off. Over-irrigation error increases to 9-13%. Further improvement is necessary to use this sensor suite in almonds. Even though MLR analysis gave high R^2 values, T_{air} was the major factor influencing the equation. The small size of almond leaves coupled with an earlier version of the IR sensor that was available when experiments were conducted in almond orchards could have been the reason for less than optimal results in almonds. In 2011, we are planning to use a more advanced sensor (Model 6000L, Everest Interscience, Tucson, AZ) that emits a visible light beam through the sensor's lense covering the exact same field of view of the IR sensor. Therefore, leaf temperature of small target leaves such as those of almonds can be measured more accurately.

Table 3. Results from stepwise selection discriminant analysis.

Exposure	Error rate (%)			Prediction (%)				Significant parameters
	Stressed	Unstressed	Total	Correct	Wrong	Critical error	Over irrigation	
Shaded	27.7	13.0	20.3	79.0	21.0	15.1	5.9	T_{leaf}, T_{air}, RH, v_{air}
Sunlit	29.7	16.7	23.2	76.3	23.7	16.1	7.6	T_{leaf}, T_{air}, RH

Table 4. Results from canonical discriminant analysis.

Exposure	Error rate (%)			Prediction (%)			
	Stressed	Unstressed	Total	Correct	Wrong	Critical Error	Over Irrigation
Shaded	24.6	27.8	26.2	74.0	26.1	13.5	12.6
Sunlit	26.6	20.4	23.5	76.3	23.7	14.4	9.3

Objective 2.

Data for light interception and yield will be used to refine the relationship shown on the graph shown 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 areaas 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 tevaluate 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.

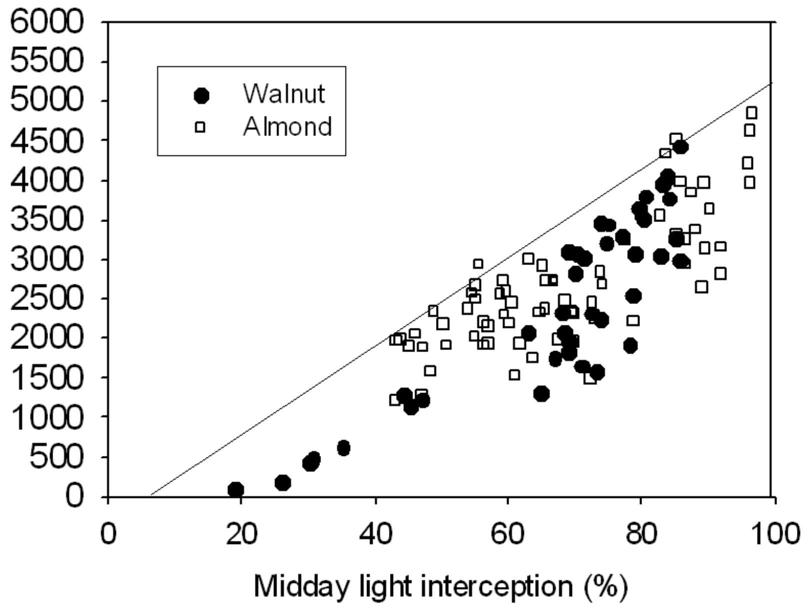

Figure 4. Midday canopy light interception versus yield relationship from various almond and walnut trials from throughout the state using hand lightbar.

Data collected with the Mule lightbar from the 20 orchards listed in **Table 1** is 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 regressions for each

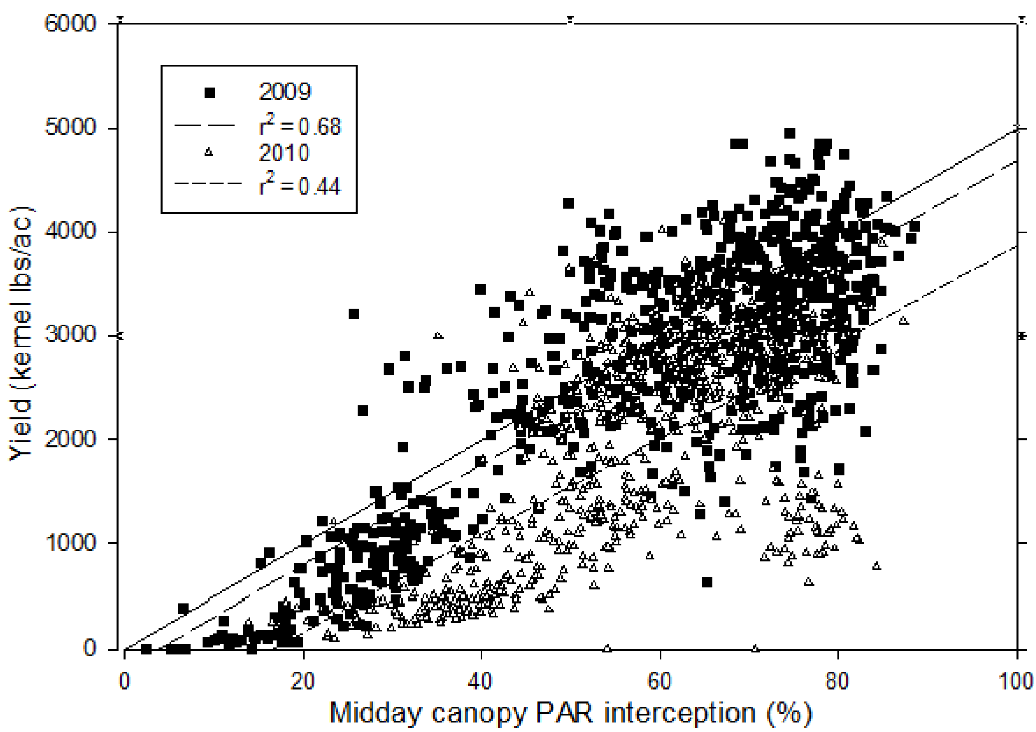

Figure 5. Midday canopy light interception versus yield relationship from mobile platform data for almond sites throughout state for 2009 and 2010 seasons.. Solid line indicates theoretical sustainable upper limit while dashed lines indicate regression lines for each year as indicated in legend.

year are both 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 bearing potential.

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 5** shows the yield, light interception and yield per unit light intercepted for the different Nonpareil sources as well as the varieties included in a variety block near McFarland, CA. These data suggest that there is little difference in productivity per unit light intercepted among all of the Nonpareil sources. Nor were there differences in yield among the sources in 2010 except a lower yield in Nonpareil- J (**Table \5**). However, Nonpareil-J did not have significantly less yield per unit lightintercepted suggesting the trees were just a little smaller. To separate out the small potential differences among the Nonpareil sources we will have to look at many years of data to separate out alternate bearing effects, etc. Some varieties produced fewer kernel pounds per unit light intercepted suggesting there may be differences in efficiency of production for different varieties. Data for multiple years will be needed to differentiate yield efficiency variation from alternate bearing effects.

Table 5. Midday canopy light interception, kernel yield, and yield per unit light intercepted by Nonpareil source and variety for McFarland Variety trial 2010.

Variety	Midday Canopy PAR interception (%)	Yield (kernel pounds/acre)	Yield per unit PAR intercepted
Nonpareil-5	61.5 cd	3130.3 ab	50.8 a
Nonpareil-Nico	63.1 cd	3141.0 ab	49.7 ab
Nonpareil-7	66.6 ab	3281.7 a	49.4 ab
Nonpareil-6	63.4 bcd	3081.0 a	48.7 ab
Chips	57.3 e	2789.3 b	48.4 ab
Nonpareil- 38270	64.0 abc	3010.9 ab	47.1 ab
Nonpareil-Dr	61.9 cd	2849.0 ab	46.2 abc
Nonpareil- Newell	65.0 abc	2931.4 ab	45.2 abc
Nonpareil-J	62.6 cd	2736.6 b	43.8 abcd
Kahl	47.4 f	2048.1 c	43.4 abcd
Sweetheart	67.1 a	2803.0 ab	42.1 cd
Winters	50.5 fg	1945.2 cd	38.5 cde
Marcona	47.6 g	1745.1 cde	36.7 de
2-19E	59.8 de	2020.4 cd	33.7 e
Kochi	62.4 cd	1466.2 e	23.5 f

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 6**. It is clear from these data that different fumigants can both 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.

Table 6. Midday canopy light interception, kernel yield and yield per unit light intercepted by fumigation treatment and coverage, Madera County methyl bromide alternatives site 2009 and 2010.

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 c
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 site (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, 551	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, 551	8-ft strip (38%)	152	53.1 ab	1297.9 ab	24.4 a

Preliminary Conclusions:

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 with different levels of stem water potential. Empirical models were developed 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 results look promising and it is particularly interesting that shaded leaves look like they may work better than sunlit leaves. Since sunlit leaf temperature varies with leaf angle, the ability to use the temperature of shaded leaves to assess water status would be very useful. These techniques will be refined during the 2011 field season.

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 if 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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